

Modern Meteor Science

An Interdisciplinary View

Edited by

Robert Hawkes, Ingrid Mann
and Peter Brown



MODERN METEOR SCIENCE

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PREFACE

This proceedings includes a selection of review and original research papers from the Meteoroids 2004 conference held at the University of Western Ontario in London, Canada from August 16–20, 2004. The conference brought together researchers in meteor science and related fields from more than 20 different countries. The 70 papers presented in this volume represent the combined contributions of more than 150 different authors from approximately 100 different institutions.

This conference was the fifth in a series of meteoroid meetings which have been held every few years since 1992, the previous one being in Kiruna, Sweden in 2001. The next Meteoroids conference will be held in 2007 in Spain.

The conference provided a comprehensive overview of leading edge research on topics ranging from the dynamics, sources and distribution of meteoroids, their chemistry and their physical processes in the interplanetary medium and the Earth's atmosphere. Significant work related to meteoroid impact on space weather, their hazard to space technology, and laboratory studies of meteorites, micrometeorites and interplanetary dust were also well represented.

The high activity of the Leonid stream and the coordinated international campaigns spawned by the opportunities offered by the Leonid showers provided a rich observational dataset. These campaigns also lead to development of new observational and analysis techniques. Many of the contributions in this volume reflect these new techniques and observational collections.

The accurate measurement of orbits for several recent meteorite falls coupled with detailed observations and modelling of their behaviour is providing a bridge between meteoritic material studied on Earth and the composition of Near Earth Asteroids. The discovery of solid particles entering the solar system from interstellar space and improved dust measuring capabilities on interplanetary spacecraft broaden the range of experimental data connecting astrophysical dust with solar system dust. The evolution of solid matter provides a bridge to include aspect of astrobiology and astromineralogy that currently is enabled through infrared astronomical observations.

Current meteoroid research benefits from the use of large aperture radar facilities to detect smaller meteors and enhanced electro-optical techniques which have extended the size range of this technique as well as the resolution of the observations. The general availability of high powered computing

facilities to support dynamical model calculations as well as sophisticated ablation models has opened a new era in parent body – meteoroid studies. Significant progress was reported on ablation models for meteoroids ranging from dust to those producing bright fireballs.

All papers in this volume followed the same rigorous refereeing process as other papers in the journal *Earth, Moon, and Planets*. We would like to acknowledge the assistance of more than 90 different referees who played a pivotal role in improving the quality and clarity of the papers.

The scientific organizing committee (listed below) provided the scientific direction for the conference, and played a key role in defining the scientific areas to be addressed and in selection of invited speakers. We would like to thank the other members of the local organizing committee who put in so many hours of work in making sure that the logistical and technical aspects of the conference were in place and that participants could focus on the scientific discussions. The success of the conference owes much to the student assistants and the members of the Royal Astronomical Society of Canada London Centre.

The accompanying CD-ROM provides a set of photographic memories, as well as a copy of the conference abstract book which includes abstracts for all papers presented.

We would also like to acknowledge the major sponsors for the conference, including the Department of Physics and Astronomy, Faculty of Science and Vice-President's office (Research) at the University of Western Ontario, the Canadian Space Agency, and the Space Environment and Effects office and Orbital Debris program office of NASA. Their financial contributions permitted a much more inclusive and effective conference and scientific proceedings. Finally, the guest editors acknowledge the diligent work and professionalism of the editorial staff at Springer Science, and the editors of *Earth, Moon, and Planets*.

Sincerely

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POSSIBLE METEOROID STREAMS ASSOCIATED WITH (69230) HERMES AND 2002 SY₅₀

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Abstract. The orbits of (69230) Hermes and 2002 SY₅₀ are similar and the Earth approaches both of them twice: at the end of October the local orbital minimum distances are smaller than 0.007 AU, and at the end of April the distances are smaller than 0.04 AU. This gives us opportunities to observe the meteors associated with these asteroids. Using the geocentric parameters of the orbital close encounters (the theoretical radiant) and our D_N distance function (Valsecchi et al. *Mon. Not. R. Astron. Soc.* 304 (1999) 743), we searched for meteoroids originated by Hermes and 2002 SY₅₀. A search among 1830 good quality photographic meteors gave negative results: we found no meteor dynamically similar to Hermes or 2002 SY₅₀. In a second search, done in a set of 62150 radio meteors, we applied two methods (M1, M2) and in both cases we found two streams; the streams found with the M1 method had 43 and 30 members, those found with the M2 method had 39 and 14 members. However, these results do not look convincing, due to the small number of common members in the corresponding streams. We therefore conclude that amongst the IAU meteors used in our search there are no compact streams associated with Hermes and 2002 SY₅₀.

Keywords: Asteroids, meteoroid streams, Hermes

1. Introduction

On 1937, Oct. 28.9 UT, at the Königstuhl Observatory near Heidelberg, Karl Reinmuth photographed an asteroid-like object. The asteroid obtained the designation 1937 UB and was named Hermes by the Astronomisches Rechen-Institut (Schmadel, 1999). Since it was tracked for only five nights, and because of its extreme proximity to the Earth, only an approximate orbit was determined (Gondolatsch, 1937).¹ Because of the poor quality of the orbit, Hermes was lost immediately after the discovery.

¹A best fit to the observations was published in MPC 3014 of Oct 1969 by Marsden.

When asteroid 2002 SY₅₀ was discovered by LINEAR, it was noted that its orbital elements resemble those of 1937 UB, and a number of teams tried to link the two objects; however, the attempts to demonstrate the identity of Hermes and 2002 SY₅₀ failed.

On Oct. 15, 2003 Brian Skiff of the Lowell Observatory discovered an unknown object, that Timothy Spahr (see in Skiff et al. 2003) suggested to be 1937 UB, and that Chesley and Chodas (2003) successfully linked with Hermes.

Radar observations (Margot et al., 2003) have shown that Hermes is a binary asteroid, with the two components having almost the same size, and orbiting each other at a distance ~ 4 times greater than the individual radii of the components. The rotational status of the binary system is synchronous (Margot, 2004) and the total angular momentum is close to the critical one, necessary to have rotation-induced fission of a rubble pile – a process that could produce meteoroids.

The heliocentric and the geocentric dynamical parameters of Hermes and 2002 SY₅₀ are given in Tables I and II. The orbits are similar and the Earth approaches both of them twice in a year, giving us opportunities to observe the meteors associated with these asteroids: as a day-time shower in spring, and as a night-time shower in autumn.

The hypothesis that Hermes may be a parent of the Piscids meteor stream was put forward by Hoffmeister (1948); however, Plavec (1954) rejected it on the basis of celestial mechanics. Also Sekanina (1973; 1976) proposed possible associations between Hermes and several streams:

TABLE I
Heliocentric orbital elements of Hermes and 2002 SY₅₀

Orbital elements	a	e	q	ω	Ω	i
2002 SY ₅₀	1.706	0.689	0.530	99°.2	34°.6	8°.7
(69230) Hermes	1.655	0.624	0.622	92°.4	34°.5	6°.1

The reference frame epoch is J2000, the osculatig epoch is MJD = 53000 (NEODyS, 2004).

TABLE II
Calculated geocentric radiant parameters of Hermes and 2002 SY₅₀

Radiant parameters	MOID AU	Date	α_G	δ_G	V_G km/s	θ	ϕ
(69230) Hermes	0.004	Apr-27	30°.6	23°.2	18.3	90°.0	100°.1
2002 SY ₅₀	0.048	May-13	41°.1	30°.2	21.5	94°.3	103°.7
2002 SY ₅₀	0.002	Oct-29	41°.9	4°.2	21.5	94°.9	281°.5
(69230) Hermes	0.007	Nov-01	39°.2	5°.3	18.3	89°.8	279°.6

MOID is the minimum distance between the orbits of the asteroid and the Earth, close to the date indicated; the radiant coordinates α_G , δ_G give the direction opposite to the geocentric velocity V_G that the asteroid; θ , ϕ are the Öpik angles characterizing the anti-radiant (Valsecchi et al., 1999). The reference frame epoch is J2000, the osculating epoch is MJD = 53000.

Piscids, δ Piscids, χ Piscids, β Cetids, ϵ Arietids, Southern Arietids, Tringulids. More recently, a certain similarity between the orbits of Hermes and of the δ Arietids was pointed out by Obruchov (1991). According to Povenmire (2004), Kronk and Terentjeva believed that Hermes was the parent body of the October Cetids; in his short note Povenmire (2004) did not share these views, and added that 2002 SY₅₀ is not related to either branch of the Cetids. Unfortunately he did not give quantitative arguments supporting his opinion.

In the present study we search the IAU meteor data files, looking for meteor streams associated with the minor planets Hermes and 2002 SY₅₀.

2. The Meteor Data and the Cluster Analysis Method

We performed three separate searches in two meteor data sets. The first search was done on 1830 photographic meteors (the same meteors as in Jopek et al. 2003), and the two other ones were done on 62150 radio meteors extracted from the IAU Meteor Data Center (Lindblad and Steel, 1993). From the original radio files we rejected all the meteors for which the internal consistency test (see Jopek et al. 2003) failed or whose orbital eccentricity $e > 1.2$. Before starting our study, all relevant orbital and radiant parameters were transformed to the J2000 reference system. We took the orbits of Hermes and 2002 SY₅₀ from NEODYs (2004), and evolved them to six osculating epochs, covering the time interval 1950–2000; these 12 orbits were used in the rest of the study.

The photographic meteors and the 24 theoretical radiants of Hermes and 2002 SY₅₀ were tested for grouping in the same way as described in Jopek et al. (2003). Namely, we applied: the D_N distance metrics (Valsecchi et al., 1999), a single linking cluster analysis technique and the similarity thresholds corresponding to the 99% reliability level of the identified groups.

In the case of the radio meteors we applied two methods:

- M1 – consisting of our D_N distance function, a cluster analysis algorithm described in Sekanina (1970), and the similarity threshold $D_c = 0.2$,
- M2 – consisting of the D_{SH} distance function by Southworth and Hawkins (1963), a single linking cluster analysis technique, and the similarity threshold $D_c = 0.145$.

As similarity thresholds we adopted the values that gave us a number of stream members similar to those obtained in the earlier searches by Sekanina (1976) or Kronk (2002).

3. Results and Conclusions

Among the 1830 photographic meteors, using values of the thresholds corresponding to the 99% reliability level, we found no single meteor associated with any radiant of Hermes or 2002 SY₅₀. Increasing the values of the thresholds by 20% resulted in one big group of 510 members which included all the Hermes and 2002 SY₅₀ radiants, as well as many Taurids, α Capricornids, κ Cygnids and sporadic meteors.

In the next two searches, amongst 62150 radio meteors, two streams associated with Hermes and 2002 SY₅₀ have been found. In Table III, we summarize the main results of the M1 and M2 searches.

TABLE III

The two meteor streams associated with minor planets Hermes and 2002 SY₅₀. The names of the streams are assigned according to the usual convention, i.e. choosing the bright star located on the sky near the the coordinates α_G , δ_G of the radiant. The third column gives the number of members identified by each method; in brackets we lists the number of common members identified by both methods. For each stream the first and second rows give the average values of parameters for the night-time and the day-time branches of the stream. The third row gives the average values of the two branches.

Searching method	Meteor stream name	M	Activity time interval	e	q AU	ω	Ω	i	α_G	δ_G	V_G km/s	θ	ϕ
M1	N-time γ Cetids	29 (17)	Oct 21–Nov 10	0.73	0.57	92°	39°	5°	40°	8°	22	91°	277°
	D-time α Arietids	14 (4)	Apr 25–May 09	0.72	0.57	88°	40°	7°	36°	19°	22	91°	98°
	S1	43 (21)	–	0.73	0.57	91°	39°	6°	–	–	–	–	–
	N-time γ Taurids	8	Oct 18–Nov 24	0.75	0.59	88°	53°	6°	53°	13°	22	89°	278°
	D-time η Taurids	22	May 09–May 27	0.75	0.56	88°	58°	6°	54°	25°	22	91°	100°
	S2	30	–	0.75	0.57	88°	57°	6°	–	–	–	–	–
M2	N-time γ Cetids	25 (17)	Oct 18–Nov 17	0.73	0.53	95°	39°	7°	43°	8°	22	94°	279°
	D-time α Arietids	14 (4)	Apr 25–May 29	0.70	0.53	89°	45°	6°	41°	19°	21	94°	99°
	S1	39 (21)	–	0.72	0.53	93°	41°	7°	–	–	–	–	–
	N-time γ Cetids	6	Oct 21–Nov 24	0.60	0.66	84°	41°	5°	39°	5°	17	88°	280°
	D-time α Arietids	8	Apr 12–May 09	0.63	0.62	90°	35°	7°	29°	24°	18	90°	101°
	S2	14	–	0.62	0.64	88°	38°	6°	–	–	–	–	–

The values of the parameters of the S1 streams identified with both methods are in good agreement. However, these groups contain only 21 common meteors. In the case of the S2 streams, the result is worse, as there are no common meteors at all. Moreover, we found that four members of the S2 group identified by the M1 method belong also to the S1 group obtained by the M2 method, and vice versa. This can be interpreted as a strong indication of an overall low reliability of the results obtained.

As mentioned earlier, the thresholds used in the M1 and M2 searches were not obtained by the method described in Jopek and Froeschlé (1997), since we had not enough computer power available to make such a determination. However, in the case of the M2 search we made an estimate of the reliability of the streams identified with several threshold values.

Using artificial meteor samples (about 100, statistically consistent with the original sample), we found that amongst 62150 radio meteors, a stream of 40 members may be identified at the 99% reliability level only if the threshold $D_c < 0.07$. Repeating the search with the M2 method, with this value for D_c , we detected only two radio meteors with orbits similar to that of Hermes.

Therefore, we have to conclude that, in the IAU meteor data set, compact meteor streams associated with the minor planets Hermes and 2002 SY₅₀ do not exist. However, due to the limitations of the statistical determination of the thresholds used in the present paper (Jopek et al., 2003), we cannot rule out the possibility that Hermes and 2002 SY₅₀ are associated with diffuse meteor streams.

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ARE ASTEROID 2003 EH1 AND COMET C/1490 Y1 DYNAMICALLY RELATED?

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Abstract. The orbit of asteroid 2003 EH1 is very similar to the mean orbit of the Quadrantid meteoroid stream so that a close relationship between the two is very likely. It has already been suggested that Comet C/1490 Y1 could be the parent of the Quadrantids. If this is the case, then some relationship between the comet and the asteroid might be expected. The orbit of C/1490 Y1 is based on a short observing arc of about 6 weeks and all the observations were with the naked eye, so that its elements are very poorly determined. Hence, forward integration to determine whether asteroid 2003 EH1 represents the re-discovery of the dormant nucleus of C/1490 Y1 is not feasible. Instead we choose to integrate back in time the orbit of 2003 EH1, which is far better determined, and a family of 3500 clones, all of which are moving on an orbit that is consistent with the present known orbit of 2003EH1. We compare the results primarily with the recorded observations of the comet rather than the orbit of the comet derived by Hasegawa. We find that one clone is consistent with these observations.

Keywords: Asteroids:individual-2003 EH1, comets:individual-C/1490 Y1

1. Introduction

The Quadrantid shower is a prolific and regular shower seen at Northern latitudes around the beginning of January. It is arguably the only major meteor shower that does not have a body that is generally accepted as being its parent. Part of the problem of identifying the parent undoubtedly lies in the fact that orbits in this region of the Solar System evolve very rapidly so that claims can be made based on a similarity of orbits at some epoch in the past. Equally, a similarity of orbits at the current time alone is not a proof of parenthood. The history of the Quadrantid meteoroid stream, including a discussion of most of the suggested parent bodies can be found in Williams et al. (2004).

One of the suggestions for the parent of the Quadrantids is comet C/1490 Y1 (Hasegawa, 1979), the claim being based on orbital similarity around AD 1490. The comet was a naked eye object between 1490 December 30 and 1491

February 15 and its positions on the sky recorded by Chinese, Korean and Japanese astronomers (Ho, 1964). Orbits for the comet, based on these observations, have been derived by Hind (1846), Peirce (1846) and Hasegawa (1979). These orbits differ significantly from each other, especially in inclination, which ranges from 52° to 105° . We give the orbital elements derived by Hasegawa (1979) as it was the latest to be derived. Here and throughout, unless otherwise stated we use equinox J2000.

$$q = 0.761, \quad i = 73^\circ.4, \quad \Omega = 280^\circ.2, \quad \omega = 164^\circ.9.$$

The observing arc is too short for the derivation of the eccentricity and Hasegawa assumed that the orbit was parabolic. Based on the possibility that C/1385U1 was the same comet, Williams and Wu (1993) suggest that a value around 0.75 was a better value for the orbital eccentricity. The orbital elements of the Quadrantid stream at the present time, given by Wu and Williams (1992) are

$$q = 0.974, \quad e = 0.684, \quad i = 71^\circ.4, \quad \Omega = 282^\circ.89, \quad \omega = 169^\circ.2.$$

As can be seen, they are quite similar.

However, it must be realized that the orbital elements of C/1491 Y1 are poorly determined and there are two main reasons for this. First, the elements are based on the observations of the comet for a single arc of approximately 6 week duration. Secondly, the observations are not precise positions and timings but descriptions of what was seen. A translation of the Chinese descriptions, taken from Ho (1964), are reproduced below. The Korean and Japanese records are similar. *31st December 1490 On a Wu-Hsu day in the 11th month of the third year of the Hung-Chih reign-period a (hui) comet appeared at the south of Thien-Chin with its tail pointing NE. It trespassed against Jen-Hsing and passed Chhu-Chiu. On a Wu-Shen day the first day in the 12th month (10th January 1491) it entered the Ying-Shih (13th lunar mansion). On a Keng-Shen day (22 January) it trespassed against Thien-Tshang.*

The orbits as determined by Hasegawa, Hind and Pierce are based only on these descriptions and any other orbit that produces a path across the sky consistent with these descriptions is an equally valid orbit for comet C/1491Y1.

It was first pointed out by Jenniskens (2004) that asteroid 2003 EH1, discovered by LONEOS, is moving on an orbit that is remarkably similar to that of the Quadrantid stream. Both Jenniskens (2004) and Williams et al. (2004) numerically integrated the orbit of asteroid 2003 EH1 published in MPEC 2003-E27 back to 1491 and found that the orbit then was similar to that of the comet. They also found that the derived orbit in 1491 was very sensitive to the orbit assumed for asteroid 2003 EH1 in 2004, so that a fairly wide range of orbital parameters were possible for the orbit in 1491.

Further observations of 2003 EH1 became available during 2004. Through the inclusion of these, a new orbit (not very different from the old orbit), but with a significant reduction in the errors, was derived. The orbital elements, taken from MPEC 2004-N22 at epoch 2004 July 14.0 are

$$a = 3.1261336, \quad e = 0.6184611, \quad i = 70^\circ.79028,$$

$$\Omega = 282^\circ.94687, \quad \omega = 171^\circ.36877, \quad M = 90^\circ.15212.$$

The question that we discuss in this communication is whether, based on the new orbit for asteroid 2003 EH1, it is dynamically related to C/1490 Y1. At first sight, this is an easy question to answer. It requires the numerical integration of an orbit for a relatively short time interval of around 500 years. However, Hughes Williams and Fox (1981) showed that the nodal retrogression rate of the Quadrantid stream was exceedingly sensitive to the assumed orbital elements. Froeschlé and Scholl (1982) went further, suggesting that the behavior of the Quadrantid stream was actually chaotic. This possibility was also explored by Wu and Williams (1992). The basic reason for this behavior is easy to see. The aphelion distance of the orbit is roughly 5.05 AU, so that small changes in this distance represents a large relative change in the closest approach distance to Jupiter. Further the orbital period is about 5.5 years so that mean motion resonances such as the 2:1, 7:3 and 9:4 with Jupiter are also all nearby. Since asteroid 2003 EH1 moves in exactly the same region of the Solar System as the Quadrantid stream, it is reasonable to assume that its dynamical behavior is also extremely sensitive to the assumed orbital elements. Thus integrating a single orbit for asteroid 2003 EH1 back in time, even if the elements are quite well determined, is likely to produce misleading results. Hence, we have replaced the single body with a family of 3500 clones and integrate the orbits of all of these clones. Williams et al. (2004) and Jenniskens (2004) have done this for the old (i.e., pre 2004 July) orbit using far fewer clones. As the region is chaotic, we believe that the far larger number of clones is necessary in order to fully sample the region.

2. The Generation of the Family of Clones

The methodology for determining the elements of each of the clones has been described by Williams et al. (2004). This method is based on the work of Chernisov et al. (1998) also described later by Bordovitsyna et al. (2001). It is also a very similar method to that used by Milani (1999). Rather than using the six orbital elements of the osculating ellipse, it uses rectangular coordinates and the corresponding velocities, the traditional position-velocity six dimensional phase space. The published orbit for 2003 EH1 is represented by a single point with position vector $\mathbf{q}_0$ in this phase-space while the error bars

in the observations convert into a range of values for each of the six coordinates (in effect a covariant matrix). A Gaussian distribution is generated for each coordinate with mid point at the value of the appropriate element of $\mathbf{q}_0$ and standard deviation corresponding to the value of the error bar. The probability of selecting a particular value for one component of the position vector $\mathbf{q}$ for a clone is then determined from these Gaussian distributions. This means that more clones are generated with values close to those of the nominal orbit of 2003 E1 and fewer at the extremities of the error box.

Phase-space positions for 3500 clones were generated in this manner and the motion of each clone was then integrated back to 1490 AD using the Everhart 19th order procedure with variable step length. The end product of the integration is the velocity and position of the clone at the given time. This can then be converted to an osculating ellipse for any equinox. We have chosen to use J2000 with the epoch being the termination date of the integration.

3. Comparison Between the Positions and Motions of the Clones and C/1490 Y1

As we have said, the actual orbit of C/1490 Y1 is poorly determined, which makes it very difficult to compare this meaningfully with any other orbit, especially if we consider the range of values spanned by Hind, Hasegawa and Pierce. In contrast, the actual path of the comet across the sky is more firmly known. Thus, it is more sensible to compare the motion of our clones across the sky in 1491 with the observed data rather than comparing orbital elements. We thus calculate the positions of the clones on the sky (RA and Dec) at given dates around January of 1491 and compare these with the observed positions as deduced from the ancient records of the appearance of C/1490 Y1.

Figure 1 is a plot of the night sky showing the constellations mentioned in the Chinese observations (using equinox J2000) together with the positions of the 3500 clones on January 22 1491, approximately the mid point of the observing time-span. For information, we also include the path of comet C/1490 Y1 if it was moving on the orbit given by Hasegawa but with $e = 0.75$. As can be seen, the positions of most of the clones do not match the described positions of the comet, being at far too low a declination and nowhere near Jen-Hsing or Chhu-Chiu. We also note that the vast majority of the clones are, as expected, clustered about the nominal location of asteroid 2003 EH1. However there are two clones whose sky positions lie close to Jen-Hsing and Chhu-Chiu and are thus in roughly the correct location at the given date.

It is easy to understand the general features of the above results. The period from time of perihelion passage of the comet in 1491 to that of asteroid 2003 EH1 in 2003 is almost exactly 512 years. The orbital period of asteroid 2003 EH1, calculated from its semi-major axis is 5.527 years.

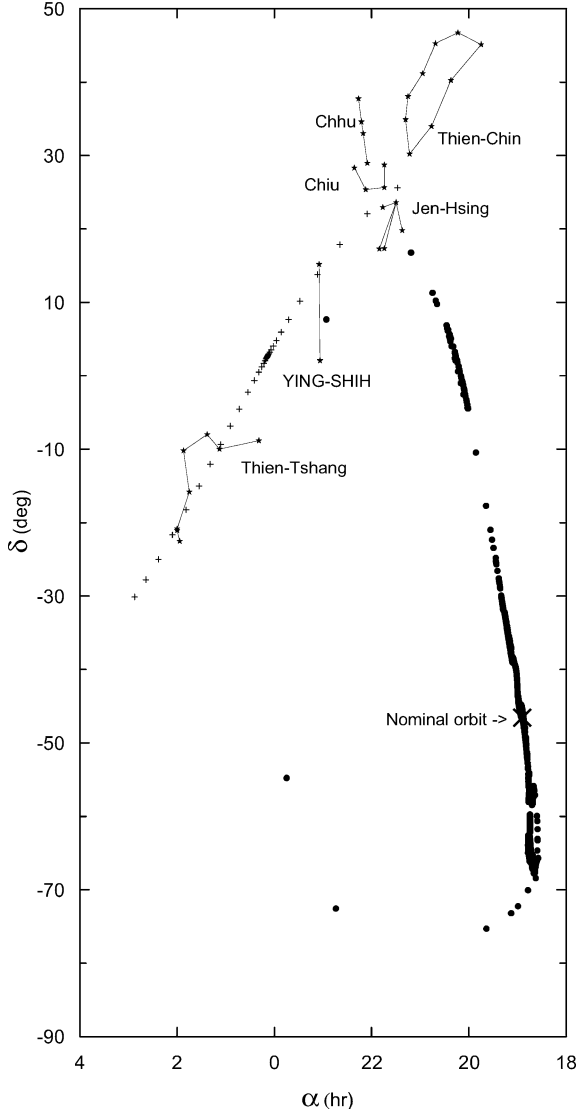


Figure 1. Positions on the sky of asteroid 2003 EH1 at its nominal position, together with the positions of the 3500 clones on 1491 January 22, also shown is the path of comet C/1490 Y1 according to Hasegawa.

A simple calculation shows that, if the period had remained exactly constant throughout the interval of interest, in January 1491, the asteroid would have completed 92.6 orbits and thus be close to aphelion rather than perihelion. A further simple calculation shows that the spread in the initial orbital period of the clones caused by the minor changes in orbital parameters alone is less than 10^{-6} years, which produces almost no

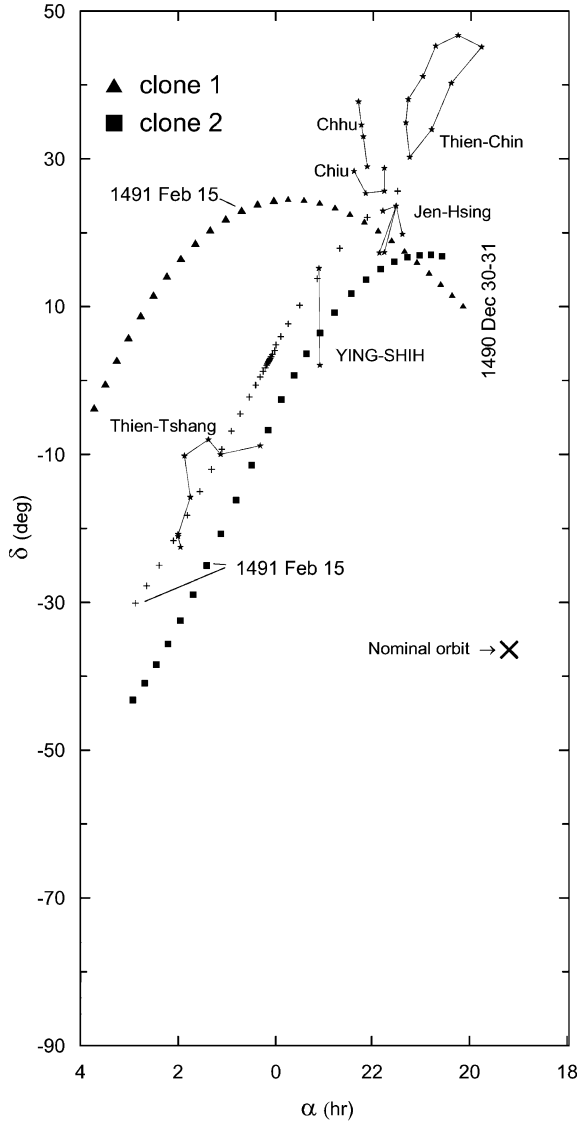


Figure 2. The path across the sky between 1490 December 30 and 1491 February 15 of the two clones that were close to the position described for the comet, that is around Jen-Hsing and Chhu-Chiut on 1491 January 22. Also shown is the path of comet C/1490 Y1 according to Hasegawa.

difference in the mean anomaly compared to that of 2003 EH1. This is roughly what we find in Figure 1, with most of the clones and the asteroid at low declination (which corresponds to near aphelion). The results in this figure also supports a conclusion we reached earlier, namely that the region is chaotic so that small initial changes become exaggerated. The

clones that are at high declination, and thus near perihelion, are in such a position because of perturbations to their orbit from the Planets. Hasegawa gives the date of perihelion passage of the comet as 1491 January 6. Our best fit clone has a perihelion passage date of 1491 January 15. Other clones that are near the correct region of the sky as shown in Figure 1 have perihelion passage dates at 1491, January 15, 1491 February 15 and two near 1491 March 15. It is impossible to calculate the probability of orbits being perturbed in this way, this can only be determined through numerical experimentation. With our results, we are into statistics of small numbers and, if an answer is required, either many more clones need to be investigated or the initial orbital distribution of the clones must be varied so that the majority of the clones do not have orbital values close to the mean.

Being in the correct location on one date is not sufficient, the sky positions should match throughout the 6 weeks of observations. In Figure 2 we show the paths of these two clones across the sky between 1490 December 30 and 1491 February 15. The Chinese Constellations and the path taken by the comet according to Hasegawa (1979) are also shown. As can be seen, the path of one of the clones (shown as black triangles) is much higher in the sky than described path of the comet. It does not 'enter Ying-Shih' but passes above it nor does it 'trespass against Thien-Tshang', again passing above it. The clone is also late in time, being above Ying-Shih on February 15 rather than in Thien-Tshang. The path of the second clone is a much better fit to the descriptions of the apparition, the only slight discrepancy being that the path passes two or three degrees below Jen-Hsing rather than 'trespassing against it'. It is also close to the Eastern wall of Thien-Tshang on February 15.

Though we are basing our comparisons primarily on the path across the sky, it is interesting to compare the orbital elements of this clone with those given by Hasegawa for the comet in 1491 and also for the Quadrantids as given by Williams and Wu (1992) for 1491. Those for the comet have already been given but are repeated for convenience. The orbital elements of the clone have been rounded to the same number of significant figures as those of the comet.

$$\text{clone } a = 3.08, \quad e = 0.82, \quad i = 65^\circ.5, \quad \Omega = 286^\circ.2, \quad \omega = 163^\circ.9.$$

$$\text{comet } a = 3.04, \quad e = 0.75, \quad i = 73^\circ.4, \quad \Omega = 280^\circ.2, \quad \omega = 164^\circ.9.$$

$$\text{Quadrantids } a = 2.94, \quad e = 0.74, \quad i = 70^\circ.5, \quad \Omega = 284^\circ.0, \quad \omega = 164^\circ.3.$$

This shows that there is similarity between the orbits, but by no exact fit between any pair of derived orbits.

4. Conclusions

We have compared the paths across the sky of 3500 clones of asteroid 2003 EH1 with the descriptions given by Eastern Astronomers of the apparition of comet C/1490 Y1 in early 1491. It is clear that the position of asteroid 2003 EH1 on the sky, using the best fit orbit available in July 2004 does not match the position on the sky of the comet, being far to low. However one of the clones of 2003 EH1 does provide a fit to the comet observations.

Most of the spread in the possible positions on the sky in 1491 comes about because of the effects of perturbations by the planets on the orbits, primarily causing a change in period so that the body is close to perihelion rather than being with the bulk of the clones close to aphelion. These changes in period can come about through only a very small change in the initial orbit since small changes become exaggerated because of the perturbations.

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THE PROBLEM OF LINKING MINOR METEOR SHOWERS TO THEIR PARENT BODIES: INITIAL CONSIDERATIONS

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Abstract. Efforts to link minor meteor showers to their parent bodies have been hampered both by the lack of high-accuracy orbits for weak showers and the incompleteness of our sample of potential parent bodies. The Canadian Meteor Orbital Radar (CMOR) has accumulated over one million meteor orbits. From this large data set, the existence of weak showers and the accuracy of the mean orbits of these showers can be improved. The ever-growing catalogue of near-Earth asteroids (NEAs) provides the complimentary data set for the linking procedure. By combining a detailed examination of the background of sporadic meteors near the orbit in question (which the radar data makes possible) and by computing the statistical significance of any shower association (which the improved NEA sample allows) any proposed shower–parent link can be tested much more thoroughly than in the past. Additional evidence for the links is provided by a single-station meteor radar at the CMOR site which can be used to dispel confusion between very weak showers and statistical fluctuations in the sporadic background. The use of these techniques and data sets in concert will allow us to confidently link some weak streams to their parent bodies on a statistical basis, while at the same time showing that previously identified minor showers have little or no activity and that some previously suggested linkages may simply be chance alignments.

Keywords: Asteroids, comets, meteor showers, meteor radar

1. Introduction

Much work has been done in attempting to link minor meteor showers to their parent bodies. Major meteor showers have been exclusively associated with comets, with the exception of the Geminids and Quadrantids which are generally considered to be linked to bodies currently displaying no cometary activity (3200 Phaethon and 2003 EH1). Are some minor showers connected to weak or faint comets or even to extinct comets? The question of whether asteroids might be associated with minor showers is of particular interest. Efforts to find the parent bodies of minor showers have been impeded primarily by two factors: the incompleteness of our knowledge of the near-Earth asteroid/comet population and the scarcity of accurate meteor orbits for weak showers. The first problem has been alleviated over the last decade as the sample of near-Earth asteroids (NEAs) has grown considerably due to the activity of large surveys such as Spacewatch, the Lincoln Near-Earth Asteroid Survey (LINEAR) and the Lowell Near-Earth Object Search

(LONEOS). As of this writing there are over 2800 known NEAs, defined as having perihelia $q < 1.3$ AU (Minor Planet Center, <http://cfa-www.harvard.edu/iau/mpc.html>) and 1516 single-apparition and 155 multi-apparition comets (Marsden and Williams, 2003). The second difficulty, that of obtaining accurate orbits for minor showers, has been addressed by the success of meteor patrol radars such as the Advanced Meteor Orbit Radar (Baggaley, 2001) and the Canadian Meteor Orbit Radar (Webster et al., 2004). The latter has collected over one million meteor orbits over the last 2 years and continues to accumulate them at a rate of about 2500 a day. It is this data set that we will use in our analysis. Using these two new data sets and a multiplicity of criteria for making stream–parent associations, the links between meteor showers and their sources can be made with confidence.

2. The Canadian Meteor Orbit Radar (CMOR)

The Canadian Meteor Orbit Radar (CMOR), located at 43.2° N, 80.7° W near Tavistock, Ontario, is described in detail by Webster et al. (2004). The radar measures several thousand meteoroid orbits per day to a limiting radio magnitude of +8 or an equivalent meteoroid radius of approximately 100 microns. The velocity for all echoes detected at three separate sites is measured using the time-of-flight technique (cf. Baggaley 2002). Comparison with major meteor showers that have known out-of-atmosphere velocities allows correction for atmospheric deceleration and yields a final mean velocity error of order 5% in the individual velocity measurements. Errors for each orbit are computed based on the measured errors in the time delays.

3. Criterion 1: Checking the background

A complicating factor in the study of minor showers is the ever-present sporadic background. Is a group of measured meteor orbits a true shower or a simple statistical fluctuation in the background flux of meteors? In order to disentangle the two phenomena, good measurements of the (non-uniform) background are needed. What is needed is to search for enhancements in the meteoroid orbit density in the five-dimensional orbital element space and determine if these are sufficiently elevated above the density seen at nearby orbits. CMOR provides the wide-coverage and long-time baseline data set needed to reliably extract weak showers from the background as the large data set reduces the statistical noise dramatically.

In order to search for enhancements in the meteor flux, we adopt the technique presented by Steel (1995) of computing a restricted D criterion based only on a , e and i for an asteroid against a sample of meteoroid orbits,

and plotting the result versus longitude of perihelion ϖ . The restricted D criterion used is (Asher et al., 1994)

$$D^2 = \left(\frac{a_1 - a_2}{3}\right)^2 + (e_1 - e_2)^2 + \left(2 \sin \frac{i_1 - i_2}{2}\right)^2. \quad (1)$$

The procedure is as follows. Some arbitrary asteroid orbit is selected. The D parameter above (which does not include the angular elements) is computed between this test asteroid orbit and *all* the meteoroid orbits in the database. All the asteroid–meteor pairs with D below some cutoff value (in this case we arbitrarily choose $D < 0.2$) are kept. A histogram (Steel uses a polar plot but we find a histogram is more useful given the size of the dataset involved) is then constructed of the number of meteoroid orbits that pass our low- D filter, as a function of the meteoroids' ϖ . In effect this procedure asks the question, “At any given ϖ , how many meteoroids have orbits with a , e and i close to that of the asteroid in question?” This provides a measure of the sporadic background as, for most values of ϖ , any meteoroids with low D values are simply sporadics which are only coincidentally associated with our test asteroid orbit. If an enhancement exists at the longitude of perihelion of the asteroid itself, however, this indicates a possible excess of orbits consistent with meteoroids being produced recently (i.e. within one precession cycle) from the asteroid itself. This method is designed to find young showers that have suffered little or no orbital evolution. Older streams, having undergone significant differential orbital precession from their source, will not be detected by this technique.

This work is still ongoing, but we present here some of our initial results. Figure 1 shows the outcome for two NEAs, 1998 SH2 and 2004 HA1. Both show an uneven and varying background, but with small distinct enhancements at the location of the asteroids' longitude of perihelion (shown by the vertical line).

Once enhancements in the orbital distribution have been extracted, the full D parameter (in practice, we use the D' parameter of Drummond (1981) rather than the standard D of Southworth and Hawkins (1963)) between likely source asteroids and the nominal orbits of meteor showers can be computed, and a search made for small values of D indicating possible associations.

This is usually the first step (and the only one that can be performed in the absence of a large meteor orbit database) in most shower association studies, but here it is motivated initially by the results of the radar data. Table I lists a few NEAs with observed radar enhancements and nearby minor showers (Cook, 1973), along with their Tisserand parameter T_J relative to Jupiter and their relative D' (Drummond 1981).

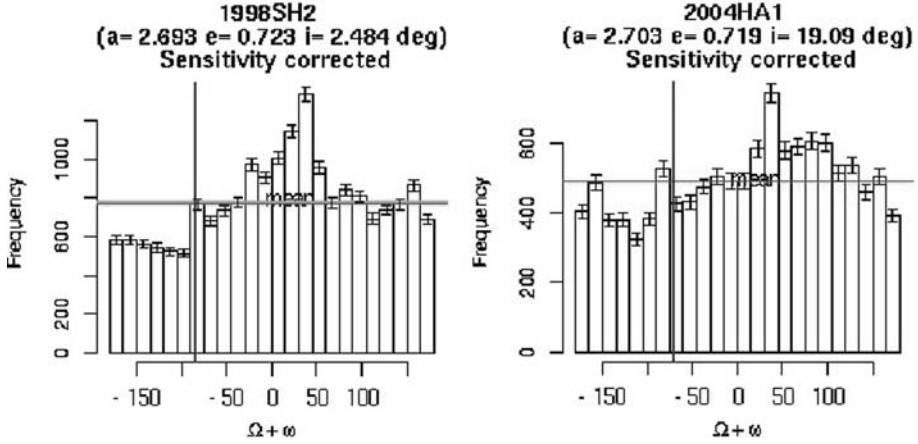


Figure 1. Histograms of the number of meteor orbits from the CMOR data base with $D < 0.2$ with respect to two NEAs, as a function of ϖ . The vertical line indicates the longitude of perihelion of the asteroid, the horizontal line the average number of orbits per bin. The uncertainties shown on the histogram bars are $\sqrt{N}$ to give an indication of the statistical noise. The meteor numbers have been weighted to compensate for the varying collecting area of the radar for radiant at different declinations.

TABLE I

A few NEAs with an observed excess of meteor orbits in their vicinity that lie near known minor showers (taken from Cook (1973))

	a	e	q	i	ϖ	T_j	D'
2004 HA1	2.704	0.719	0.759	19.1	288.1	2.870	
α Bootids	2.586	0.710	0.750	18.0	283.0	2.955	0.028
1998 SH2	2.693	0.723	0.745	2.5	274.3	2.924	
σ Leonids	2.206	0.660	0.750	1.0	276.0	3.336	0.048
2002 EX12	2.603	0.767	0.606	11.3	34.2	2.887	
α Capricornids	2.565	0.770	0.590	7.0	36.0	2.917	0.050

4. Statistical Significance

Though an asteroid orbit lies near that of a minor shower, their proximity might simply be a coincidence. What is the probability that the orbit of an asteroid will, by chance, lie near that of a meteor shower? This depends on the distribution of asteroid orbits in the vicinity of the shower orbit. Particularly near the ecliptic, the possibility of a chance alignment is significant.

Given a potential asteroid–shower combination differing by D'_0 , we can ask, how many other asteroids have $D' < D'_0$? If this number is large, the probability of a mere chance association is large. If the number is zero, we

can still ask the question: given a distribution Y of N asteroids, what is the probability that a random selection from Y would have resulted in an asteroid closer to the shower than our chosen asteroid (i.e. that our randomly chosen asteroid has $D' \leq D'_0$)?

To answer this question, we turn to Monte Carlo techniques. We choose asteroids at random from the de-biased distribution of asteroid orbits (described below) until we select one that has $D' \leq D'_0$. The number n of trials required to do so provides a measure of the probability of a chance association. This procedure is repeated one hundred times and we consider the average number of trials $\langle n \rangle$. We define expectation value of the number of asteroids closer to the shower orbit than our test asteroid to be $P = N/\langle n \rangle$. If this number is much greater than one, then more than one asteroid is at least as well aligned with the shower as our test asteroid, and so a chance alignment becomes more probable. If this number is less than one, P represents the probability that another asteroid is closer to the shower than our chosen asteroid. A small value of P implies there are few other asteroids in the phase space around the shower, and thus that a chance alignment is unlikely.

Of course, even if the probability of a chance association is high, this does not exclude the existence of a real association between the stream and the asteroid. Nevertheless, it gives us a measure of whether an association is likely to be coincidental or not (assuming the stream is young, much less than a precession cycle in age).

Here we make use of the de-biased NEA distribution as determined by Bottke et al. (2002). From an examination of the Spacewatch program discoveries and recoveries and knowing the biases and sensitivities of the survey, they extrapolated from the observed distribution of NEAs to the real one. It is that distribution that we use here as a basis for estimating the probability P_d , where the subscript indicates we are using the de-biased distribution. We also compute the probability P_0 on the basis that the observed distribution is in fact the real one, as a secondary check.

Table II lists the results obtained for two previous shower–asteroid associations. The link between the Geminids and Phaethon ($D'_0 = 0.018$) is

TABLE II

Two previous associations of meteor showers (Cook, 1973) with asteroids (Whipple, 1983; Hasegawa, 2001)

	a	e	q	i	ϖ	T_j	P_0	P_d
Geminids	1.36	0.896	0.142	23.6	225.3	4.23		
3200 Phaethon	1.271	0.890	0.140	22.2	227.4	4.51	0.00014	0.00065
α Capricornids	2.53	0.77	0.59	7	36	2.94		
2101 Adonis	1.874	0.765	0.441	1.35	33.0	3.55	13	85

A value of $P > 1$ indicates the number of objects with $D' \leq D'_0$. See the text for details.

found to be extremely unlikely to be a mere chance alignment. However, the α Capricornids and 2101 Adonis ($D'_0 = 0.16$) are much more likely to be only coincidentally aligned, as there are 13 objects observed to have lower D' relative to that shower than Adonis, and the de-biased distribution predicts that there may be as many as 85 with smaller D' ultimately found.

For those possible associations mentioned earlier we find that for the α Bootids–2004 HA1 ($D'_0 = 0.028$) pair, $P_0 \approx 0.001$ and $P_d \approx 0.012$; for σ Leonids–1998 SH2 ($D'_0 = 0.047$), $P_0 \approx 0.19$, $P_d \approx 0.5$ and for the α Capricornids–2002 EX12 ($D'_0 = 0.051$), $P_0 \approx 0.069$ and $P_d \approx 0.3$. That means that (based on the de-biased distribution) there is a 1 in 83 chance that there is another asteroid closer to the α Bootids than 2004 HA1, a 1 in 2 chance that there is an asteroid closer to the σ Leonids than 1998 SH2, and a 1 in 3 chance for a better match than 2002 EX12 to the α Capricornids.

As a caveat, we note that this approach depends to a large extent on the stream orbit being well-known, which is not usually the case for weak showers. We will need to refine this work with improved stream orbits, which can be extracted from the CMOR orbit data set. We plan to do so by constructing a phase space density from the CMOR data set using the techniques of Welch (2001). This procedure converts the distribution of discrete orbits into a continuous distribution. It is then a simple matter to determine the locations of the density peaks near meteor showers, these peaks corresponding presumably to the best-fit orbit for the shower as a whole. Also needed is a consideration of the de-biased comet distribution. The probabilities computed above do not allow for the possibility that the source body is a comet and this will affect the computed statistical significance of any association.

5. Conclusions

Linking weak showers to their parents can be done with confidence given a sufficiently complete set of meteor orbits and near-Earth objects. A procedure which includes three tests is discussed. First, Steel-type plots as a function of longitude of perihelion allow the sporadic background to be assessed. Second, the D' parameter allows the nearness of a body's orbit to that of a shower to be determined. Third, Monte Carlo simulations allow the statistical significance of any hypothetical associations to be examined. The convergence of several different lines of evidence, each unconvincing on its own, allows stronger conclusions to be made. We also note that the existence of certain minor meteor showers has yet to be shown conclusively and it is hoped that the large CMOR dataset, with sensitivity at larger masses where showers are highly visible, will help remove some of this uncertainty.

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EVOLUTION OF THE GEMINIDS OBSERVED OVER 60 YEARS

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Abstract. Visual observations collected over 60 years (1944–2003) are analysed. The profiles and values of the population index near the activity peak are rather constant over the entire period and confirm the strong mass segregation within the stream. The peak activity is characterized by a plateau in the profile with a ZHR between 120 and 130 lasting for about 12 h between $\lambda_{\odot} = 261.5^{\circ}$ and 262.4° (J2000). This is consistent with an age of the Geminid stream of about 6000 years. The position of this plateau is constant. Variations of the ZHR by more than 10% within the peak period are found in data of well-observed returns. These structures of about 0.2° duration can be traced over more than a decade with an average drift of about -0.02° in solar longitude per year.

Keywords: Geminids, meteoroid stream

1. Introduction

The Geminids is one of the strongest permanent meteor showers currently visible on Earth. A peak ZHR of 120–130 combined with the geocentric entry velocity of 34.4 km/s reflects a high number density in the meteoroid stream. Furthermore, the bulk density of the meteoroids is found to be considerably larger than for other streams. These facts and its relation to (3200) Phaethon, which is a candidate for an extinct cometary nucleus, causes a peculiar interest in the Geminids.

Observational data as well as theoretical modelling of the stream indicate that the stream crosses the Earth's orbit only from the early 19th century onwards. The Geminids and their parent are orbiting the Sun on a short periodic orbit with a period of 1.43 years. Hence we may expect that evolutionary processes which happen during a few orbital periods become visible when analysing a long-term data sample.

2. Data Sample and Meteor Magnitude Analysis

The present analysis is based on visual observations of more than 600 observers worldwide over 60 years, or about 42 orbital periods of (3200) Phaethon. The method of observation and analysis has been shown in detail

by Brown and Rendtel (1996) for the Perseids. Recent changes refer to the improvement of the determination of the population index r (Arlt, 2003). The total sample comprises 196,156 Geminids observed within 6806 h. Surprisingly, we found no data from 1959 to 1971. For the analysis we distinguished between Geminid observations obtained without moonlight interference (rate peak occurring about ± 6 days around New Moon) and with moonlight disturbance. Moonlit conditions lead to much smaller samples and are known to affect the observer's perception (Rendtel and Brown, 1999; Arlt, 2003).

Only data for individual observers were used (no group counts). The standard observing technique (Brown and Rendtel, 1996) is in use worldwide since 1988. Many data prior to 1988 have been transformed into this format. In order to avoid effects from different analysing procedures, we used only raw and no pre-processed data. The only exception regards magnitude data prior to 1960 because these were not published. Instead, we used the r -profile published by Porubčan et al. (1980). Based on the result that the r -value of the Geminids around their rate peak did not change between 1970 and 2003, we derived a systematic deviation of $\Delta r = -0.47$ of the early r -values and shifted these accordingly. In fact, this shift does not affect structures in the rate profiles, but would lead to higher ZHRs. Variations in r occur mainly in the pre- and post-peak periods. From all selected profiles (1991, 1993, 1996, 1998–2001) we find minima of r at $\lambda_{\odot} = 261.92^{\circ} \pm 0.03^{\circ}$ ($r = 2.18 \pm 0.12$), at $\lambda_{\odot} = 262.12^{\circ} \pm 0.05^{\circ}$ ($r = 1.92 \pm 0.04$), and a last one at $\lambda_{\odot} = 262.4^{\circ} \pm 0.06^{\circ}$ ($r = 1.75 \pm 0.06$). The error margins indicate that smaller variations in the region before $\lambda_{\odot} = 261^{\circ}$ are probably insignificant. The average profile of the population index r shown in Figure 1 can be regarded as a reference profile. The ZHRs presented in the next step, how-

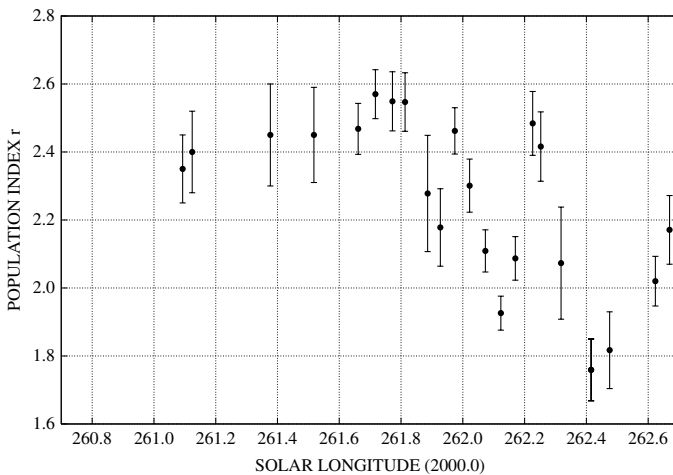


Figure 1. Average r -profile from the moonless returns 1991–2001.

ever, have been calculated with the r -values derived from the respective Geminid return.

It is generally known that the period close to the end of the ZHR-maximum is characterized by a larger portion of brighter Geminids. This corresponds with the latest r -minimum listed above. The archive of the IMO's Fireball Data Center (FiDaC) lists bright fireballs for the entire interval between $\lambda_{\odot} = 260.88^{\circ}$ and 264.02° with no obvious peak. Hence, the r -minima are caused by particles in the magnitude range between about $+2$ mag and -6 mag due to mass segregation (Fox et al., 1983) while objects brighter than about -8 mag are obviously not related to the mass-sorting effects.

3. ZHR variations

3.1. GENERAL RATE PROFILE

In a first attempt to find systematic changes of the Geminid activity, we sampled the data of moonless returns occurring in 10-year bins (until 1990) and 5-year bins (from 1991) as summarized in Table I. Only intervals with a maximum correction factor $C \leq 5.0$ (for limiting magnitude and clouds) and a minimum radiant elevation $h_R \geq 20^{\circ}$ are selected. ZHRs were calculated with a zenith exponent $\gamma = 1$. Applying $\gamma = 1.30$ resulted in a significantly larger scatter and higher ZHRs.

The Geminid peak activity level expressed in terms of the shower's ZHR has not changed between 1944 and 2003. A slight increase from about 120 ± 10 to 130 ± 10 is still within the error margins. The position of the maximum activity plateau (with ZHR peaks at both ends) is between $\lambda_{\odot} = 261.5^{\circ} \pm 0.15^{\circ}$ and $262.4^{\circ} \pm 0.05^{\circ}$ within the 60 years of data. The width of about 0.9° in Solar longitude is consistent with an age of the order of

TABLE I

Geminid data sample per collection period: number of contributing observers, observed number of Geminids, total observing time and number of moonless returns analysed

Period	Observers	Geminids	Obs. time (h)	Returns
1944–1949	10	3054	102	3
1953–1958	28	7851	225	3
1972–1980	33	5888	226	4
1981–1990	207	26,956	1082	4
1991–1995	292	58,896	1994	2
1996–2000	448	74,061	2551	3
2001–2003	137	19,450	626	1
	> 600	196,156	6806	20

6000 years for the stream (Jones, 1985). A double peak as seen in Figures 2 and 3 is expected from Jones' work (1985) as well as from Ryabova (2001).

3.2. FINE STRUCTURES

In all analyses of the near-peak activity we used a binning interval length of 0.08° in Solar longitude shifted by 0.04° corresponding to a temporal resolution of approximately one hour which allows to detect short-term fluctuations in the stream.

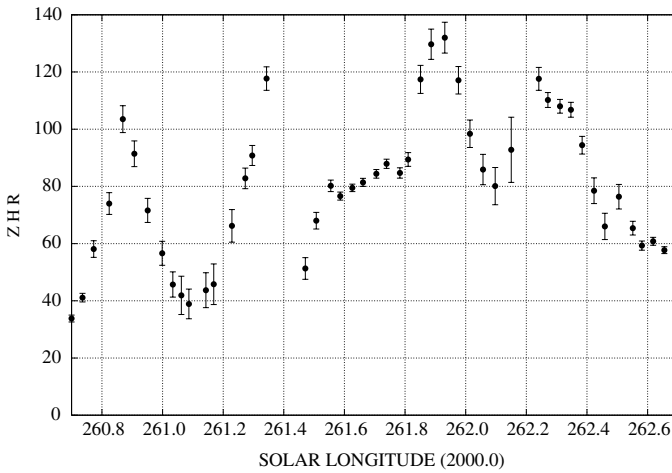


Figure 2. ZHR profile of the 1991 Geminids.

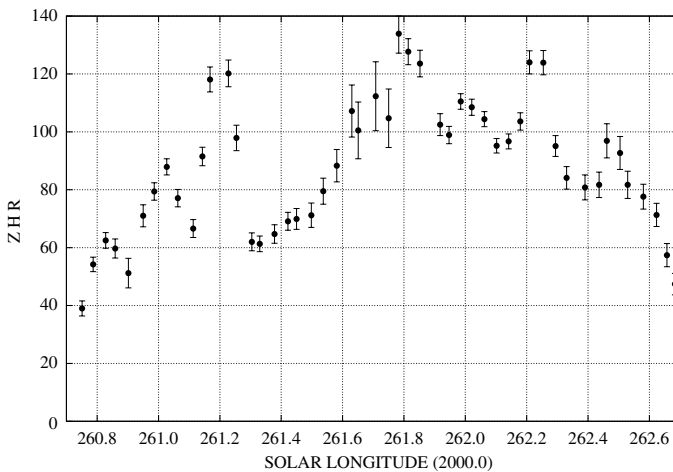


Figure 3. ZHR profile of the 1993 Geminids.

As an example, we show the ZHR profiles of the 1991 and 1993 returns (Figures 2 and 3). It was carefully checked that features in the ZHR profiles do not correspond with geographic situation of observing sites with a systematic change in the radiant elevation when another continent rotates into the observing window. Again, applying a zenith exponent of $\gamma > 1.0$ does not change the profiles but only the peak ZHR values and the scatter. Visible fine structures show an amplitude of at least 10% of the ZHR peak value. In superposed profiles (several consecutive returns) small structures of about 0.2° (approximately 5 h) duration with a slight shift from one return to the next may be averaged out (Rendtel and Brown, 1999).

Altogether, we can trace five peaks in the ZHR profiles from 1988 onwards showing a slow shift of about -0.02° per year (approximately 0.5 h) towards lower Solar longitudes (Figure 4).

4. Discussion

Because the Geminids are on a short periodic orbit, no low-order resonances are to be expected. Planetary perturbations are one possibility for such structures, but we may also see remains of particle ejections at different revolutions of the parent. More probably, different ejection trails are subsequently disturbed by the planets and cause the Earth to cross the structures at different positions. The drift implies that structures may disappear and possibly new ones appear. For example, the “latest peak” at $\lambda_\odot = 262.4^\circ$ is not visible before about 1980. This implies that new structures should become visible, especially in the range of the descending branch of the ZHR profile.

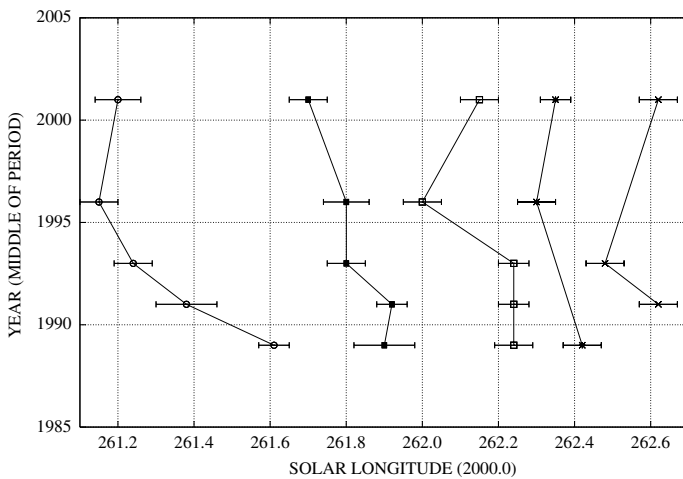


Figure 4. Shift of the sub-peaks in the ZHR peak period between 1988 and 2003.

5. Conclusions

The population index r near the Geminid peak is remarkably constant between 1944 and 2003 and shows three minima close to the ZHR maximum period at $\lambda_{\odot} = 261.92^{\circ} \pm 0.03^{\circ}$ ($r = 2.18$), at $\lambda_{\odot} = 262.12^{\circ} \pm 0.05^{\circ}$ ($r = 1.92$), and a last one at $\lambda_{\odot} = 262.4^{\circ} \pm 0.06^{\circ}$ ($r = 1.75$). The first r -minimum coincides with a peak of the ZHR, while the latest occurs just at the begin of the ZHR descent.

The main ZHR peak plateau occurs between 261.5° and 262.4° with a $\text{ZHR} \geq 120$ with little changes over the 60 years. This includes the positions of all minima of r . The width is consistent with an age of the stream of the order of 6000 years (Jones, 1985).

We can trace five ZHR sub-peaks with a typical duration of 0.2° (≈ 5 h) and an amplitude of at least 10% of the ZHR peak value. This yields drift of about -0.02° (≈ 0.5 h) per year. The long-term behaviour remains ambiguous because no annual ZHR profiles with sufficient temporal resolution are available before 1988.

Fine structures in the Geminid meteoroid stream may be caused by particle ejections at different revolutions of the parent object and by planetary perturbations. Noting the drift direction, new structures are expected to become visible near the end of the ZHR peak plateau.

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ADVANTAGES OF SEARCHING FOR ASTEROIDS FROM LOW EARTH ORBIT: THE NEOSSat MISSION

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Abstract. Space-based observatories have several advantages over ground-based observatories in searching for asteroids and comets. In particular, the Aten and Interior to Earth's Orbit (IEO) asteroid classes may be efficiently sought at low solar elongations along the ecliptic plane. A telescope in low Earth orbit has a sufficiently long orbital baseline to determine the parallax for all Aten and IEO class asteroids discovered with this observing strategy. The Near Earth Object Space Surveillance Satellite (NEOSSat) mission will launch a microsatellite to exploit this observing strategy complementing ground-based search programmes.

Keywords: Asteroid, asteroid searching, Aten, IEO, microsatellite mission, NEOs, NEOSSat spacecraft, NESS project, observing parallax

1. Introduction

The last two decades have seen a remarkable increase in the discovery rate of asteroids and comets, and, in particular, near-Earth asteroids (NEA's). The near-Earth population of small bodies is also known as near-Earth objects (NEOs) to acknowledge that both extinct and active cometary nuclei occur amongst the near-Earth population. The NEAs are divided into the Interior to Earth's Orbit (IEO), Aten, Apollo, and Amor classes, based upon their current osculating orbital elements (Shoemaker et al., 1979; Michel et al., 2000). Aten asteroids have semi major axes (a) < 1 AU and aphelion distances (Q) > 0.983 AU, Apollo asteroids have $a \geq 1$ AU and perihelion distances (q) ≤ 1.017 AU, Amor asteroids have $a > 1$ AU, $1.017 < q \leq 1.3$ AU. The "Interior to Earth's Orbit" (IEO) class is one recently coined by Michel et al. (2000) to describe the asteroid population with orbits entirely interior to that of the Earth's orbit. IEO asteroids have $a < 1$ AU and $Q < 0.983$ AU and so never cross Earth's orbit. Two IEO's have recently been discovered (the first IEO, 2003 CP₂₀, was discovered by the LINEAR team early in 2003), but the characteristics of this class remain to be well constrained.

Asteroids and comets are objects of considerable interest: (1) as primitive objects dating from the origin of the Solar System they contain an unrivalled record of Solar System formation; (2) the fraction of the small body population in Earth-crossing orbits constitutes a hazard in that several percent of these bodies will eventually impact the Earth; (3) the fraction of the population that is dynamically close to the Earth constitutes an extraterrestrial resource of diverse compositions. The NEOs that are of greatest and/or most practical interest as exploration targets, threats, and resources, constitute a common fraction of the NEO population. These objects are in Earth-like orbits; that is the necessary orbital character for NEOs with low rendezvous velocities and large likelihoods of impacting the Earth. Amongst the orbital classes only the Aten and Apollo classes are Earth crossing, so potentially

hazardous objects are confined to these classes, but low rendezvous delta-velocity (Δv) objects will also occur amongst the Amor and IEO classes.

Observing techniques, technologies, and strategies for asteroid searching (e.g., Stokes et al., 2002; Stokes, Yeomans et al., 2003) and associated observing biases (e.g., Jedicke et al., 2002) have been discussed by many researchers. Most asteroid search discussions have focused on ground-based searches, but space-based sensors are beginning to be considered (e.g., Carroll et al., 2000; Tedesco et al., 2000; Stokes, Yeomans et al., 2003; Cellino et al., 2004; Hildebrand et al., 2004). Traditional opposition searches are particularly effective at discovering the Apollo and Amor classes of NEOs, less effective at discovering Atens, and incapable of finding IEOs. Aten asteroids are most efficiently discovered by searches along the ecliptic plane at low solar elongations (e.g. Boattini and Carusi, 1998; Jedicke et al., 2002). Members of the IEO class may also be found by ground-based searches along the ecliptic at low solar elongations (e.g., Masi, 2003). The low Δv fraction of the NEO population is also most efficiently sought along the ecliptic plane near the Sun with the most favourable solar elongations dependent upon the limiting magnitude of the survey (Chesley and Spahr, 2004). Discovering the low Δv objects is a slow process for traditional opposition surveys, even if the objects come to opposition during a given close approach with the Earth, because they have intrinsically long synodic periods.

A visible light telescope in a suitable low Earth orbit (LEO) may continuously search regions near the Sun both ahead of and behind the Earth (e.g., Hildebrand et al., 2004). Such a space-based search mission is currently in design with launch planned for 2008. Defence Research and Development Canada (DRDC) and the Canadian Space Agency (CSA), will use innovative microsatellite technology to build the Near Earth Object Surveillance Satellite (NEOSSat) to track artificial satellites in high Earth orbit (e.g., Wallace et al., 2004), and to discover, track, and study NEOs (This component is termed the Near Earth Space Surveillance (NESS) project.) The spacecraft design has been strongly influenced by the successful operation of the Microvariability and Oscillations of Stars (MOST) microsatellite space astronomy mission (Walker et al., 2003). This paper briefly discusses the advantages of asteroid searching from LEO with a visible light sensor as is envisaged for the NEOSSat spacecraft.

2. Advantages of a Low Earth Orbital Telescope

Advantages of an orbiting telescope in searching for asteroids are listed in Table I. Some of these advantages are unique to an orbiting telescope so that, regardless of the number and capability of telescopes on the ground, an orbiting telescope will always have some unique capabilities that will

TABLE I
Advantages of an orbital telescope in searching for NEOs

-
1. Can look closer to Sun than ground based observatories.
 - (i) Can discover IEO's and constrain population characteristics sufficiently to better answer other questions such as impact rate on Venus.
 - (ii) Can accelerate discovery rate for NEOs, particularly for Aten class.
 - (iii) Can conduct searches for inner planet and terrestrial Trojan objects.
 - (iv) Can create flyby opportunities for spacecraft missions to interior planets.
 - (v) Can discover low delta-v asteroids years before closest approach allowing "sprint" missions/novel sample return opportunities.
 - (vi) Can observe cometary behaviour closer to Sun than otherwise possible, and will be able to monitor suspected near-extinct comets near perihelion.
 - (vii) Able to extend arcs for nearby fast movers.
 - (viii) Can create radar-imaging opportunities in daylight sky.
 - (ix) Can make virtual observations (interrogate impact keyholes) in daylight portion of sky.
 2. Twenty four hour duty cycle because removed from weather and night-time-only observing restriction.
 - (i) Able to extend arcs for nearby fast movers.
 3. Orbiting platform has > Earth-diameter observing baseline.
 - (i) Parallax determination of interesting objects is immediate and knowledge of object distance removes orbital ambiguities.
 4. Some low Earth orbits have eclipse geometries enabling observing very close to Sun using the Earth as an occulting disk.
 - (i) Able to observe possibly inwards to the orbit of Mercury ($\sim 22^\circ$ solar elongation).
-

complement ground-based observing programmes. Similarly, ground-based observing activities may complement space-based search programmes.

Stokes, Yeomans et al. (2003; Report of the Near-Earth Object Science Definition Team) reached a similar conclusion in that they rated a search telescope in Earth orbit the most effective as a single instrument versus ground-based instruments. A 1.0 m diameter LEO telescope was found as effective at cataloguing asteroids as three 4 m ground-based telescopes; the LEO telescope was also found to be superior to other space-based deployment options as a warning system (and better than the ground-based option of three 4 m telescopes). Even a 0.5 m LEO telescope substantially outperformed a ground-based 4 m telescope at both cataloguing and warning. If a search telescope can be space-based for a cost comparable to (or less than) the cost of a sizable ground-based telescope, it will represent more favourable economics as an asteroid discoverer (Dollar cost/discovery) aside from its unique capabilities. The NEOSSat spacecraft instrument is expected to have a 0.15 m-diameter mirror, presuming that the telescope design undergoes only the minimally necessary modifications from the 15 cm aperture f/6 Rumak–Maksutov design of the MOST spacecraft (Walker et al., 2003). This

instrument has a $0.86^\circ \times 0.86^\circ$ field of view and a $1,024 \times 1,024$ CCD as its focal plane science imager, so it is not as capable at searching (nor as costly) as the systems considered by Stokes, Yeomans et al. (2003). However, serendipitously, its design turns out to be an reasonable compromise for the highest value surveying that can be done from Earth orbit: a search along the ecliptic at low solar elongations. Near-Sun observing is hindered by sky background from the zodiacal light, but the strawman NEOSSat telescope design is an effective compromise between individual pixel and image field angular sizes. Simulation indicates that based upon photon counting statistics, at 45° solar elongation on the ecliptic, a telescope of this size can reliably detect asteroids at 19.5–20th V magnitude, depending upon the instrument's focal plane image characteristics and pointing stability of the spacecraft. Observing effects such as stellar clutter and trailing losses will negatively impact the detection rate (as in all surveys). The zodiacal light sky background reduces the limiting magnitude ~ 0.5 magnitudes, but the effect varies with pixel size, image width and shape, and pointing stability.

In addition to complementing ground-based searches, the near-Sun search possible with an orbiting telescope has other advantages. Observing at low solar elongations benefits from a geometric perspective effect that concentrates asteroids onto a relatively restricted part of the sky as illustrated in Figure 1, that plots an empirical distribution of Aten-class asteroids on the sky.

This Boattini and Carusi (1998) figure illustrates the geometric effect that in the sky near the Sun the greater distance between NEAs and the Earth results in their “being squeezed” into the region of sky centred on the ecliptic. This effect is particularly strong for the Aten class, but also holds for Apollos, Amors, and Main Belt Asteroids (MBA) to a lesser extent. Consequently these are rich search fields with high densities of asteroids per square degree. These search fields have the draw back that any given asteroid is fainter due to greater distance and smaller illuminated phase than typical for the same asteroid in an opposition search, but a telescope with sufficient limiting magnitude will compensate for these unfavourable considerations.

The IEO population will also be accessible within the NESS strawman search areas. Masi (2003) suggested a ground-based search from 50 to 80° solar elongation and within 10° latitude of the ecliptic plane. His simulated ground-based searches were able to discover dozens of these objects in two decades of observing. The NESS project will be approximately 10 times more efficient in discovering IEOs, as NEOSSat is able to look closer to the Sun, and will have an order of magnitude greater observing availability.

Opposition searches routinely discover asteroids passing particularly near the Earth with a range of relative velocities; these objects are interesting targets for spacecraft missions or ground-based research. The low delta- v asteroids are attractive rendezvous mission targets. However, a consequence of their low relative velocity is that they have long synodic periods, so will not

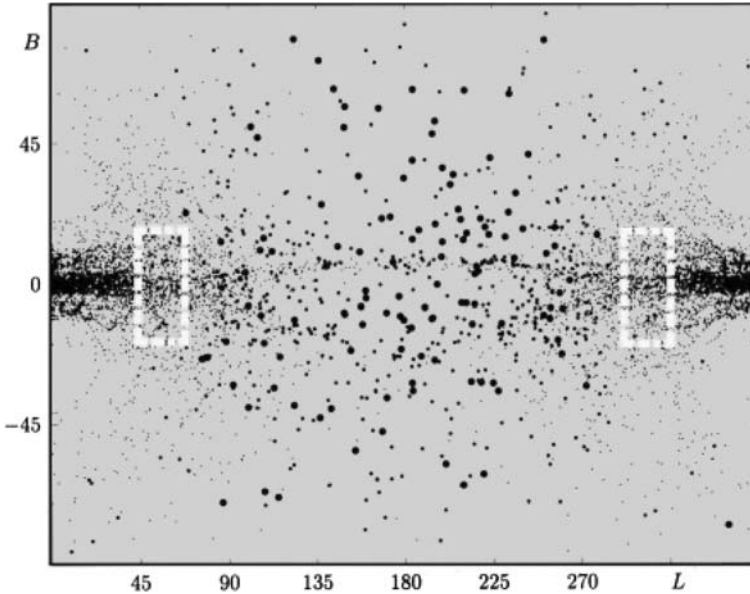


Figure 1. Strawman NESS search regions (as dashed boxes) superposed on a statistical sampling of Aten asteroid locations on the sky. (x axis plots heliocentric longitude with 180° at opposition; y axis plots ecliptic latitude) Dots represent Aten locations; size of dots indicates Aten apparent magnitudes. NESS strawman search fields as discussed by Hildebrand et al. (2004) are centred on the ecliptic at $45\text{--}70^\circ$ solar elongations. Modified from Boattini and Carusi (1998).

return to the Earth's vicinity for several decades in the extreme cases. Also, subsequent encounters rarely bring them as close to the Earth, as objects are statistically more likely to be encountered when brightest due to favourable geometry. The NEOSSat spacecraft will be looking ahead and behind the Earth, so will discover these “low and slow” asteroids before, sometimes years before, they reach the vicinity of the Earth. This will allow preparation of observing programmes, or a new style of spacecraft mission that has been termed a “sprint” mission. The latter will consist of rapid rendezvous/flyby with a NEA while it is in the vicinity of the Earth. This mission profile is favourable for manned missions as well, as the most challenging aspects of multi-year mission lengths need not be addressed.

The NEOSSat spacecraft, like all spacecraft orbiting the Earth, will have an observing baseline with length slightly larger than the Earth's diameter. An analogous if somewhat smaller baseline is in theory available to ground-based observatories, but is only rarely exploited by pairs of observatories. Motion across this orbital baseline results in determination of the parallax for observed NEOs. Figure 2 shows the discovery distances of simulated objects for Aten and IEO class asteroids using the strawman observing

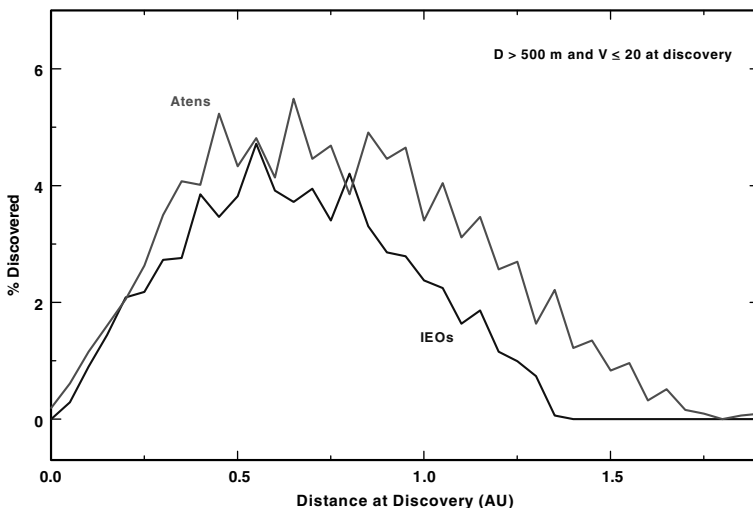


Figure 2. IEO and Aten class discovery distances in the simulated population for diameters > 500 m and discovery magnitudes < 20 . Note that Aten class asteroids are discovered to greater distances due to the larger aphelia possible for this class.

strategy from Figure 1. The simulation is based upon the population model used by Tedesco et al. (2000).

The orbital motion results in a maximum possible observed parallax of ~ 18 arcsec for objects at 1 AU distance. Given that the simulated astrometric precision of individual NEOSSat observations will be roughly 1.5 arcsec, and that two sets of images will be collected for each discovered NEO on two successive orbits with approximately half orbit baselines, meaningful parallaxes can be determined for all Atens and IEOs observed. Discovering asteroids, in particular NEAs, is substantially complicated by the abundance of MBAs with which they may be confused. Any object with an ecliptic longitude rate greater than $+75$ arcsec/h could be regarded as an NEA because only 1.5% of the MBAs in a strawman survey region (Figure 1) move faster than this. However, simulation based upon the population model of Tedesco et al. (2000) indicates that the detectable asteroids during a typical month number approximately 40 IEO's, 67 Atens, and 438 Apollos in a survey region versus $\sim 21,000$ MBAs. So, even if only 1.5% of the MBAs have NEO-like motion rates, ~ 315 MBAs are indistinguishable at discovery based only upon their proper motions. Given the consideration that NEOSSat will have to do its own astrometric follow-up for at least part of the discoveries (as ground-based instruments are restricted in observing at low solar elongations), the burden of tracking MBAs long enough to determine their orbits would decrease NEOSSat operating efficiency. Identification of NEOs by ground-based searches suffers from the same difficulty.

The identification confusion at low solar elongations is compounded as greater than usual orbital ambiguities exist for such discoveries, requiring longer arcs to adequately refine an orbit sufficiently for discrimination of orbit class. This identification problem may, however, be solved at discovery using parallax determinations enabled by the orbital observing baseline.

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DYNAMICAL RELATION OF METEORIDS TO COMETS AND ASTEROIDS

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Abstract. We tested four criteria used for discrimination between asteroidal and cometary type of orbits: Whipple criterion K, Kresak criterion Pe, Tisserand invariant T and aphelion distance Q. To estimate their reliability, all criteria were applied to classify the 2225 orbits of NEAs and 582 orbits of comets, for several epochs spanning the time interval of 40 thousands years. The Q-criterion produced the smallest number of exceptions and has shown the best stability. The biggest number of exceptions and the biggest variations are obtained for the K-criterion. We applied the Q-criterion to classify meteor orbits from the IAU Meteor Data Center and the video meteor orbits available on the Web sites. Among the sporadic radar orbits, as well as among the mean orbits of meteor streams a strong preponderance of asteroid-type orbits was observed. In case of the photographic and video meteors a weak preponderance of cometary and asteroidal orbits was found, respectively.

Keywords: Asteroids, comets, meteoroids

1. Introduction

In the Solar System, asteroids and comets are two potential sources of meteoroids. The cometary origin of meteors is beyond all doubt because of a number of known comet—meteor shower associations and abundance of meteor orbits with high eccentricities and inclinations. But there are few convincing cases of asteroidal origin.

This rises a question about the proportion of asteroidal to cometary meteors. It's difficult to discriminate reliably between asteroidal and cometary meteors from their behaviour during their interaction with the earth's atmosphere. Therefore, orbital characteristics appear to be the most suitable path to solve this problem. There are various criteria which have been applied to the problem of discrimination between the asteroidal and cometary type of orbits, as well as to the problem of classification of meteoroids. In Table I, the main results of such classification obtained in a few studies are presented. As one may see, the proportion of asteroidal and cometary meteoroids varies.

TABLE I

Proportion of asteroidal M_A and cometary M_c meteoroids among different meteor samples, determined by several authors

Source	Meteor proportion	Meteor sample
Whipple (1954)	$M_c = 80\text{--}90\%$	small camera meteors
Cepilecha, (1967)	$M_c = 46\%$	Super-Schmidt meteors physical parameters
Jacchia et al.(1967)	$M_c = 99.8\%$	Super-Schmidt meteors, orbital parameters
Steel (1996)	$M_c > M_A$	the IAU photographic meteors
	$M_c \approx M_A$	Canadian TV meteors
	$M_c < M_A$	radio meteors, Kharkov, + 12 ^m limit. mag.
	$M_c > M_A$	radio meteors, Adelaide, + 6 ^m limit. mag.
Voloshchuk et al. (1997)	$M_c = 25\%$	stream component and
	$M_c = 63\%$	sporadic component of Kharkov radio data

There are several reasons for it: the mass distributions of cometary and asteroidal meteoroids need not to be the same, different representation of the two components may be observed at different levels of meteoroid brightness. And also, different results may be obtained when different criteria are applied.

The main purpose of this study was to test these criteria for reliability and stability, and then, to apply them to classify the meteors attainable in the IAU Meteor Data Center and on the Web.

2. Criteria and Testing Procedure

We tested the following four criteria:

- K-criterion derived by (Whipple, 1954)

$$K = \log[Q(1 - e)^{-1}] - 1 \geq 0 \quad (1)$$

where: e - eccentricity, Q - aphelion distance, and $K < 0$ for the asteroids and $K > 0$ for the comets,

- Pe-criterion, the product of period of revolution and eccentricity by (Kresak, 1967)

$$Pe \geq 2.5 \quad (2)$$

where $Pe < 2.5$ for the asteroids and $Pe > 2.5$ for the comets,

- Q-criterion, that is aphelion distance Q proposed by (Kresak, 1967)

$$Q \geq 4.6 AU \quad (3)$$

where $Q < 4.6$ AU for the asteroids, $Q > 4.6$ AU for the comets,
 – and T-criterion, Tisserand invariant with respect to Jupiter

$$T = a^{-1} + 2A_j^{-3/2}a^{1/2}(1 - e^2)^{1/2} \cos I \quad (4)$$

where, A_j – semi-major axis of Jupiter; a, e – the orbital elements of the small body considered; I – inclination with respect to orbital plane of Jupiter. In this case $T > 0.58$ was taken for the asteroids and $T < 0.58$ for the comets (Kresak, 1967).

All the above criteria, except Tisserand invariant, were derived on the empirical basis—just to minimize the number of exceptions not obeying the criterion, and the simplicity of the formula (see Figure 1).

To find which of these criteria gives the smallest number of exceptions we classify 2656 NEAs and 582 comets taken from (NEODyS, 2004) and (Marsden and Williams, 2003), respectively. In Table II, one can see that the criteria (1), (2), (3), (4) are not equivalent, and that the Q-criterion seems to be the most reliable for the asteroidal as well the cometary population. Because these criteria are merely formal, not taking into account the

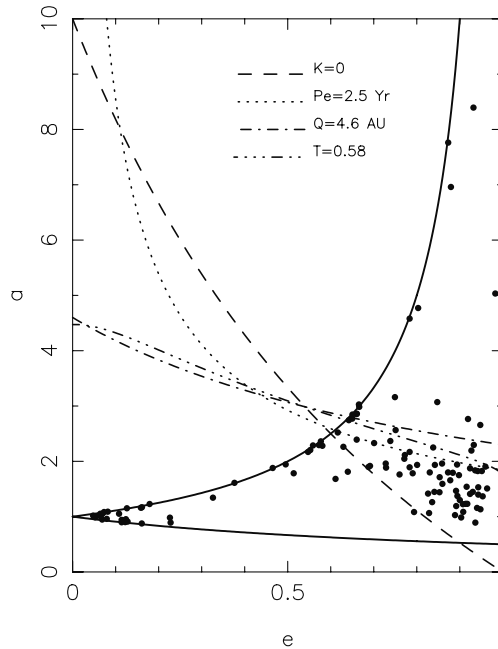


Figure 1. Distribution of meteor streams (filled circles) in the a - e plane. Continuous lines represent a boundary condition for crossing the earth's orbit; remaining lines represent four criteria given by equations (1), (2), (3), (4). On the bottom right, in the region occupied by meteor streams, K-criterion by (Whipple, 1954) runs clearly below remaining criteria. Undoubtedly, it corresponds to the significant differences between the proportion of the cometary streams noticeable in Table III.

TABLE II
The number of exceptions not obeying the cometary-asteroidal orbital criteria

Q[%]	T [%]	Pe [%]	K [%]	
4.2	7.9	11.2	17.2	among 2656 asteroids
0.7	1.5	4.8	17.8	among 582 periodic comets

potential evolution of orbits, we wanted to check how the results of these classifications are changing with time.

Our testing procedure was straightforward forward: a) we integrated numerically the orbits of 2225 NEAs¹ and 582 periodic comets; the time interval was 40 thousands years, we included the nine planets (Standish, 1998) and purely Newtonian force model; b) at several moments of time all minor bodies were classified according to the four criteria mentioned above.

On Figure 2 we present the main results of our test—the abundances of classification failure versus time in years. In the case of the Q-criterion we observe the smallest amount of failures over the entire 40 thousands years. On the other hand, the highest number of failures one may see for the K-criterion.

3. Classification of Meteoroids

In the next part of the study, all criteria were applied to classify the meteoroid orbits. We used the IAU MDC photographic and radio data (Lindblad and Steel, 1993), Canadian video orbits (Hawkes et al., 1984), (Jones and Sarma, 1985), photographic and video meteors observed by members of the Dutch Meteor Society (Betlem et al., 1998, 2000) and video meteors recently published by (Koten et al., 2003). Before using them, all data were checked for internal consistency and transformed to the same reference frame J2000. Also, we excluded all parabolic and hyperbolic orbits. The resulting set of 65737 meteors was tested for stream membership by a single linking cluster analysis, the orbital distance function by (Southworth and Hawkins, 1963), and the orbital similarity threshold $D_c=0.07$. We detected 121 streams, and the stream component included 15% of the meteor sample.

Next, using all four criteria we made two classifications: among the sporadic meteors and among the mean orbits of the meteor streams. We present the results in Table III.

¹ In this part of our study we used a sample of 2225 NEAs orbits only.

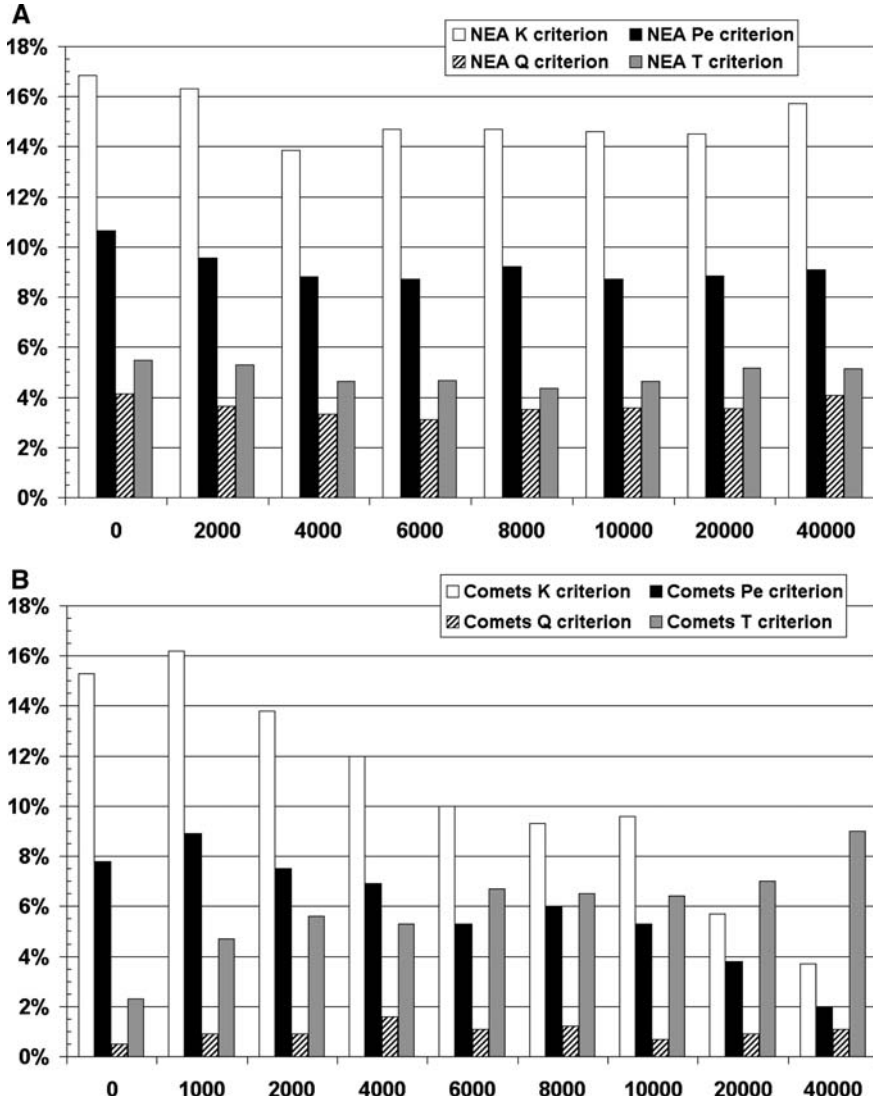


Figure 2. Results of the cometary – asteroidal orbital criteria testing; percentages of the NEAs-comets classification failures versus time in years. As one may see, for both populations over 40 thousands years the Q-criterion gives the smallest number of exceptions.

4. Conclusions

In the present study, we have shown that among the four orbital criteria, the Q-criterion is the most reliable tool for dynamical discrimination of the NEOs population. It failed only for ~4% of the known NEAs and for less than 2% of the periodic comets. The high reliability of this criterion is on its

TABLE III

Proportion of cometary orbits among the sporadic meteoroids and the stream component. In the separate rows we give the percentages of meteors classified among the whole sporadic component, among radar, photographic and video meteors, respectively. The last row contains the proportion of cometary orbits among the mean orbits of meteor streams

Q [%]	Pe [%]	T [%]	K [%]	—
<i>Sporadic meteoroids</i>				
23.6 (0.2)	28.7 (0.8)	35.5 (0.6)	42.8 (4.4)	55891 all meteoroids
22.2 (0.0)	27.1 (0.5)	34.0 (0.3)	41.4 (4.2)	52993 radio
51.7 (2.4)	62.4 (4.1)	60.2 (2.9)	71.7 (3.5)	1677 photographic
46.9 (0.5)	54.2 (1.2)	64.9 (0.3)	63.6 (2.0)	1221 video
<i>Meteoroids streams</i>				
16.5 (5)	24.0 (5)	24.8 (7)	66.9 (17)	121 streams

The values given in round brackets represent deviations between the values on the left and the percentages obtained after introducing the random noise to the orbital parameters q, e, i —perihelion distance, eccentricity and inclination, respectively. The normal noise with $\sigma_q = 0.01$ AU, $\sigma_e = 0.1$, $\sigma_i = 2$ deg was introduced for all meteoroids, from the radio sample and meteoroid streams. In case of the photographic and video meteoroids we substituted $\sigma_q = 0.005$ AU, $\sigma_e = 0.05$, $\sigma_i = 1$ deg.

stability over the 40 KYears time period. We found the K-criterion to be of the lowest reliability.

Using the Q-criterion we have found that among all sporadic meteors of our sample: 78% of radio meteors, 48% of photographic meteors and 53% of video meteors moved on the orbits of the asteroidal type. In the case of the mean orbits of meteoroid streams, 83% of them are of the asteroidal type.

We have found markedly less cometary orbits among the photographic meteors than (Whipple, 1954) and (Jacchia et al., 1967)—these authors used the K-criterion. Concerning the photographic and video meteor samples, our estimations are consistent with those given by (Steel, 1996). Also, similar to (Voloshchuk et al., 1997) we have found a small proportion of cometary type orbits among the mean orbits of meteor streams. However, in the case of sporadic radio meteors, we have obtained opposite results to (Voloshchuk et al., 1997). Namely, we found that 78% of meteors moved on asteroidal type orbits, (Voloshchuk et al., 1997) found only 37% (see Table I and III). At the moment, we cannot explain this discrepancy, hence so we leave this problem open. Of course we are aware that our results cannot be considered final; we see at least two important limitations in our study: we didn't take into account the observational selections; and we didn't include the non-gravitational effects in our numerical integration.

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METEOR STREAMS AND COMETS

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Abstract Recent progress on the interrelation between meteor streams and comets is reviewed both on dynamical and physical aspects. The topics include the recent concept of the structure of meteor streams, resulted success of the prediction of the meteor storms, and the recent observational situation on the cometary dust grains and meteoroids. Two possible explanations for the origin of the meteoroids together with the implication for the relation between the birthplace of the parent comets and the meteoroids are discussed.

Keywords: Comets, meteoroids, meteor stream, meteor shower, dust, dust trail

1. Introduction

The interrelation between comets and meteor streams is one of the important topics in the meteor science. Although the trials for identifying parent bodies to a certain meteor shower have been performed for long time, the one of the recent progress in this field is that the understanding on the structure and the evolution of each meteor stream. The resulted dust trail theory provides a strong tool for predicting the meteor shower activities for certain meteor streams, if the orbit of the parent comets can be estimated precisely. The triumph of the application to a representative meteor stream, Leonids, is introduced in the second section. The application of this theory to the other meteor streams has been carried out, and resulted in a fruitful success in several meteor showers. The examples and results are described in the third section. This situation suggests that the strong possibilities of further accumulations of the data in the meteor science by planned observations of other meteor streams when we know the orbital information of the parent comets.

The relation between comets and meteoroids is the other important topic because the meteoroids are thought to be inclusions frozen at the early stage of the solar system, and to have been kept long time inside the parent bodies. Such thermally unprocessed components may be used as an important measure for clarifying the physical and chemical situation of the proto-solar nebula at the formation of these bodies. In the fourth section, the present status of the understandings on the physical aspects of both gaseous and dust

components of comets are described. In this perspective, we introduce that we may be able to regard the meteoroids as one of the fossils suggesting formation history of such pristine solar system bodies.

2. Triumph of Dust Trail Theory

One of the recent successes of the theoretical works on meteor streams is the dust trail theory, which has made us possible to predict the activity profile of a certain meteor shower when we know the orbit of the parent comet. As the detailed concept of this dust trail theory is described by Asher (1999), we do not spend many words on the details in this paper. The basic idea for this theory was already proposed by Stoney and Dowling (1899) more than hundred year ago. They stated that the Leonid meteor streams consisted two components; one was widely spread background component, and the other was a narrower trail making sharp peaks. They named the former as Clino, and the latter as Ortho. Until the recent Leonid activity, we do not pay any attention to possible Orthos' component, and many predictions of the peak time of the meteor shower activities have been done based on the general Clino's concept that widely spread over the latest orbits of the parent comets. However, the actual situation is not so simple. The orbits of the parent comets are different for each return due to the planetary perturbations together with the non-gravitational forces. Therefore, the every return of a parent comet makes a particular narrow trail of meteoroids, which is slightly different with the older trails. Such narrow trails of meteoroids consists of a meteor stream, and this is exactly the situation of Orthos' stated by Stoney and Downing (1899). It was Kondrat'eva and Reznikov (1985) that the concept of the dust trails of meteoroids was first used for predicting the time of the peak activity of the Leonids. This approach had been widely known by the paper written by McNaught and Asher (1999). While the predicted time of the Leonids 1999 was 2h08m, the observed peak time was $2\text{h}02\text{ m} \pm 2\text{m}$ on November 18 UT, 1999 (Arlt et al., 1999a). This coincidence of the peak time within 10 min was enough for us to recognize a new era of the meteor astronomy.

In Leonids 2000, three predicted peak times have been pointed out as 7h51m on November 17, 3h44m and 7h51m on November 18 (McNaught and Asher, 1999), due to the 1932, 1733 and 1866 trails, respectively. The actual peaks were observed as 8h07m on November 17, 3h24m and 7h12m on November 18 (Arlt and Gyssens, 2000).

In Leonids 2001, four predicted peak times have been also suggested as 7h51m on November 17, 9h55m–10h28m, 17h24m–18h03m, and 18h13m–18h20m on November 18. (Brown and Cooke, 2001; Lyytinen et al., 2001; McNaught and Asher, 2001), due to the 1932, 1766, 1699 and

1866 trails, respectively. The actual peaks were observed as $10\text{h}39\text{m} \pm 4\text{m}$ and $18\text{h}16\text{m} \pm 4\text{m}$ on November 18 (Arlt et al., 2001). In Leonids 2002, two peak times have been predicted to occur at 04h00m and 10h30m on November 19 (Jenniskens, 2002; McNaught and Asher, 2002; Vaubaillon, 2002), due to the 1767 and 1866 trails, respectively. The actual peaks were observed at 04h03m and 10h49m on November 17 (Arlt et al., 2002; Abe et al., 2003). The comparison between the predictions and the actual observed peak time is summarized in Table I, which is the evidence of the triumph of the dust trail theory.

3. Application to Other Meteor Streams

The success of the dust trail theory for predictions of the Leonids activities does convince us its effectiveness to the cases of the other meteor streams. In 2000, Jenniskens and Lyytinen (2000) gave an alert for the possible enhancement of the activities of the Ursids, which was a peculiar shower such that the outbursts have been occurred when the parent comet 9P/Tuttle was located at near the aphelion. While the predicted activity was confirmed (Jenniskens, 2000; Jenniskens and Lyytinen, 2001), several observational trials succeeded to obtain valuable data including some spectra of the meteors in this shower, and the significant role of the mean motion resonance with Jupiter was clarified on the evolution of this meteor stream (Jenniskens et al., 2002).

In 2004, two wonderful successes have been realized. One was the June Boötids, and the other was the Perseids. In the case of the June Boötids,

TABLE I
Predicted and observed activities of the Leonids between 1999 and 2002

Year	Predicted peak(s)	Observed peak(s)	ZHR at the peak	Corresponding dust trail(s)
1999	01h44m Nov. 18	01h43m Nov. 18	300?	1932
	02h08m Nov. 18	02h02m Nov. 18	3700	1899
	19h55m Nov. 18	16h Nov. 18	200	1866
2000	07h53m Nov. 18	08h07m Nov. 18	130	1932
	03h44m Nov. 18	03h24m Nov. 18	290	1866
	07h51m Nov. 18	07h12m Nov. 18	480	1733
2001	09h55m Nov. 18	10h39m Nov. 18	1620	1767
	17h24m Nov. 18	18h02m Nov. 18	2830	1699
	18h13m Nov. 18	18h16m Nov. 18	3430	1866
2002	03h56m Nov. 19	10h39m Nov. 18	1620	1767
	17h24m Nov. 18	18h02m Nov. 18	2830	1699
	10h34m Nov. 19	18h16m Nov. 18	3430	1866

Vaubailon(2004) and Sato (2004) predicted the possible enhancement of the activity at 14h–19h on June 23 due to three trails produced by 1819, 1825 and 1830. The expected broad peak was definitely recognized. This prediction provided us a rare chance to perform detailed observations of such minor meteor showers, which were normally difficult to see. Based on the prediction, several professional observational teams succeeded to obtain valuable data of the spectra of the meteors in this shower (Jenniskens, 2004; Kasuga et al., 2004). On this meteor stream, the unexpected display has been observed in 1998 (Arlt et al., 1999b), and it was also well explained by the dust trail theory (Asher and Emel'yanenko, 2002).

The other success was the Perseids 2004. Lyytinen and van Flandern (2004) and Sato (2004) independently predicted the possible existence of the extraordinary peak of the Perseids 2004 at around 20h54m on August 11 due to the 1862 trail. The peak was actually observed by many naked-eye observers at around the predicted time. These results are summarized in Table II.

These situations do not only convince the effectiveness of the dust trail theory, but also widen the chance to look for the details of minor meteor showers such as June Boötids, if we know the orbits of the active parent bodies. It should be noted that the predictions by using the dust trail theory needs the orbital elements in each return of active parent bodies in detail. In the above mentioned cases, the parent comets of the Perseids and the June Boötids are the periodic comet 109P/Swift-Tuttle and 7P/Pons-Winnecke, respectively. The orbits of both comets have been well-known so that the predictions were able to be done. Although the dust trail theory and the prediction of the enhanced activities should be definitely extended to other minor showers in order to accelerate the researches of the meteor streams, we need the identifications and orbit researches for this purpose. The important keys to the predictions are the orbital parameters including the non-gravitational forces, activity profiles of parent comets corresponding to the heliocentric distance, and if possible, the information on the meteoroids such

TABLE II

Predicted activities of the meteor showers with the dust trail theory and their observational results

Shower	Predicted peak(s)	Observed peak(s)	ZHR at the peak	Corresponding dust trail(s)
Ursids 2000	7h29m Dec. 22 8h35m Dec. 22	8h06m Dec. 22	90	1405 1392
Boötids 2004	10h–19h Jun. 23	13h30m Jun. 23	50	1819, 1825, 1830 (complex)
Perseids 2004	20h54m Aug. 11	20h56m Aug. 11	≤100	1862

as size distribution, and physical evolution of them during the orbital motion. Moreover, this theory cannot be applied to the meteor streams of the asteroidal origin, because the asteroidal streams should be produced not by the gaseous ejection but also the collision or other mechanisms. The application limit of the dust trail theory at the present is at the active comets which are thought to produce regularly emission for each apparition. Another application limit is there that the enhanced activities should be young trails, not the old trails, which cannot be applied by this theory except the particular cases of the mean motion resonance such as Ursids 2000 outbursts. The possible applicable streams are Giacobinids (21P/Giacobini-Zinner), May Boötids (related to 73P/Shwassman-Wachmann 3) and tau Puppids (26P/Grigg-Skjellerup), and the meteor stream related to the 103P/Hartley2. The impossible streams at this epoch are Quadrantids, Geminids, Taurids and several daytime meteor showers during May–July.

4. Meteoroids as Fossils of the Protosolar Nebula?

The interrelation between comets and meteor streams are often emphasized from the point of view of the direct relationship for each meteor stream and the particular parent comet as mentioned in the above sections. It is indeed important aspect, in this section we hope to point out that another aspect, which should be emphasized that the meteoroids may suggest the important information on the early history of the solar nebula because they are also the major component of comets, representative astronomical objects regarded as the fossils. Here we introduce the present status of the researches both on the gaseous and on the dust components of comets, and finally some implications for the meteoroids.

4.1. GASEOUS COMPONENT IN COMETS

Comets are generally thought to be most pristine bodies in the solar system, and are regarded as fossils of the protosolar nebula. They are divided into two major dynamical groups; Edgeworth–Kuiper Belt comets (hereafter, EKBCs) and Oort cloud comets (hereafter, OCs). The former is thought to be formed in trans-Neptunian (EKB) region at around 40 A.U., and fallen into the inner region of the solar system recently (Duncan and Levison, 1997). The latter is thought to have been born in the Jupiter–Uranus region, and ejected, by the large planets, into the almost parabolic orbit out to the Oort cloud. Therefore, these two groups are expected to have different properties physically or chemically. However, we cannot find out any definite differences of gaseous components between two categories at the first order

(A'Hearn et al., 1995). Although several subtle differences such as carbon depleted group, have been found, it seems to be unrelated to the dynamical categories. One of the difficulties is that the most of the observable comets have been processed already by the solar insolation. This may have affected the chemical components of relatively volatile gaseous species. In order to look for unaltered information among the gaseous species, several attempts have been done. Although several isotopes such as deuterium have been detected in several bright comets, the lack of samples makes us impossible to discuss the relation to the dynamical class. The nuclear spin states, the ortho and para, of the hydrogen atoms, is also thought to be invariable parameter which was fixed at the physical circumstance of the formation of the molecules. The corresponding parameter, called as spin temperature, has been derived from the ortho-to-para ratio of the water molecules for several comets. Due to the recent development of the new method to estimate the ortho-to-para ratio of the ammonia molecules (Kawakita et al., 2001), and of the water from the hot bands (dello Russo, 2004), the number of the samples are increasing. However, the derived spin temperatures of seven comets show the concentration at 30 K including EKBCs (Kawakita et al., 2004). These facts suggest that the gaseous components of comets may reflect either the well-mixed situation within the proto-solar disk at the formation phase of comets, or much earlier situation of the molecular cloud.

4.2. DUST COMPONENT IN COMETS

On the other hand, the dust grains or refractory components of comets, including meteoroids, may reflect the physical situation of the birth place of each comet. One of the hot topics is the existence of the crystalline silicates within cometary grains. The first detection of the crystalline feature at 11.2 micron subpeak was reported for comet 1P/Halley (Bregman et al., 1987). In 1987, the dust rich comet C/1987P1 (Bradfield) also showed the existence of the similar subpeak (Hanner et al., 1990). With the development of the infrared instruments, more samples in OCs have been observed until now. The origin of the crystalline silicates, which often observed in OCs as the 10-micron resonant emission feature together with the broad feature of the amorphous silicates, is still controversial (Wooden, 2000). Although the crystalline silicate feature was detected in disks around pre-main sequence Herbig Ae/Be stars (Bouwman et al., 2001) and in the debris disk around young main sequence stars such as beta Pic (Knacke et al., 1993), no spectral evidence is found in diffuse interstellar medium, molecular clouds, nor young stellar objects (Li and Draine, 2001). Therefore, it is likely that the crystalline silicates of comets were produced during or after the collapse of the presolar cloud, from the amorphous silicate of the interstellar origin. The possible mechanisms for producing

crystalline silicate grains are either condensation from the high temperature gas or thermal annealing amorphous silicates. Because both mechanisms require high temperature, these phenomena should have occurred at the inner region of the solar nebula.

On the other hand, the comets consists, basically, of low temperature materials including ices. The puzzling question is how comets could have incorporated both high- and low- temperature materials simultaneously. There are three possible ideas to explain the situations. One is the *turbulent radial mixing* or *X-wind mixing of the solar nebula* (Shu et al., 1996; Bockelée-Morvan et al., 2002), which transports the crystalline silicates produced in the inner hot region out to the cold region where the icy objects such as comets were formed. The crystalline silicate should be transported out to the Kuiper belt region at around 40 A.U. within 10^6 years by applying an appropriate solar nebula model (Bockelée-Morvan et al., 2002). Actually, Okamoto et al. (2004) discovered the concentration of the crystalline silicates in the central part of the disk of vega-like star, beta Pictoris. Although the evolutionary phase of this object is thought to be later than the comet formation, this is a clear evidence of the crystallization by the insolation of the central stars. Although this scenario of the transportation predicts that the ratio of the crystalline to amorphous silicates may depend on the heliocentric distance of the comets formed.

Alternative theory is the *in-situ annealing of the amorphous into crystalline silicates at the comet forming region by shock heating* driven in the solar nebula (Harker and Desch, 2002; Nakamoto and Miura, 2003). Because the shock heating depends strongly on the density of the nebular gas, this scenario can be applied at most 10 A.U. of the solar nebula.

Another idea is the *cool crystallization*, which converts the amorphous silicates into crystalline ones just after the ejection from the cometary nuclei within the coma (Yamamoto and Chigai, 2003). In the case of the core-mantle particles (Greenberg and Zhao, 1988), it is possible to make crystalline silicates only by the internal energy driven by the chemical reactions within the grains driven under the solar insolation. This idea depends strongly on the structure and components of the dust grains.

It should be noted that each idea may predict different result on the crystalline silicate between two dynamical groups. While the *in-situ* annealing theory by the shock heating predicts that the EKBCs should have no crystalline silicate if the transportation mechanism is not efficient, the mixing transportation or cool crystallization idea allows the EKBCs have crystalline silicate. In other words, the ratio of the crystalline to amorphous silicate ratio may be used to know what happened in the early solar nebula.

No crystalline silicate feature of EKBCs, which includes comets 67P/Churyumov-Gerasimenko, 26P/Grigg-Skjellerup, 24P/Schaumasse, 19P/Borrelly, 4P/Faye, and 69P/Taylor (Sitko et al., 2004), has been detected so far until 2004. The only positive detection is 29P/Schwassmann-Wachmann 1 by the

Spitzer telescope (Stansberry et al., 2004). It should be noted that the case of comet 103P/Hartley 2 is a little complicated. Although Crovisier et al. (1999) insisted the existence of crystalline silicate feature, Colangeli et al. (1999) could not detect any feature on this comet. Moreover, A'Hearn et al. (1995) suggested that this comet may be an interloper from OCs on the basis of the analysis on the chemical abundance. Hence we do not take this comet, nor the Halley-type comets, into the present discussion. The observational results of the detection of the crystalline feature in comets are shown in Table III. It is likely that lower rate of the crystalline feature in the EKBCs. However, this may be due to the low signal-to-noise ratio of the samples taken so far, because the EKBCs intrinsically fainter than the OCs. The lack of the samples of the 10-micron feature of the EKBCs obtained so far is mainly due to the typical observational faintness of the EKBCs. Search for the crystalline silicate feature of the bright EKBCs taken by a high quality instrument is important.

4.3. IMPLICATION TO THE METEORIODS

The dust grains or refractory components in comets may have information on the physical or chemical situation of the birth places of the parent comets. Although the above discussion of the crystalline feature is mainly for the component of the small dust grains, typically less than 10 μm , because the large particles are not warm enough to produce the silicate feature. However, the larger grains are also to be valuable to be discussed in this perspective. Especially, the meteoroids belong to the largest part of dust grains in the cometary nuclei. The meteoroids may be produced either in the physical process at the surface of the cometary nuclei due to the crust development, or by the collisional growth of the small grains within the proto-solar nebula. If the former process is dominant, the structure and the size of meteoroids may not be affected by the birth place of the parent comets, and most of the meteoroids are the similar at the first order. However, if the latter mechanism is the dominant in the formation of the meteoroids, then we may extract information on the origin of each comet.

TABLE III
Present statistics of detection of crystalline silicates in comets

Dynamical class of comets	Detection rate of silicate feature	Detection rate of crystalline feature
EKBCs	83% (5/6)	17 % (1/6)
Long period	82% (14/17)	41% (7/17)

Actually the former process has been strongly suggested in the case of smaller cometary grains. It is well-known that some 'old' comets, which experienced solar insolation for long time such as short period comets, show deficiency of smaller grains less than a few μm . Lisse et al. (2004) studied the difference of the size distribution of cometary grains within the coma for two typical comets; a relatively new Halley-type comet, 126P/IRAS and an 'old' comet 2P/Encke. They derived the higher fraction of grains larger than 20 μm in the 2P/Encke compared with that of 126P/IRAS, and attributed this fact mainly to the thermal evolution of the dust grains at the surface of cometary nuclei. However, it is not clear whether the evolution at the cometary surface makes much larger grains up to the typical size of meteoroids as 1 cm. On the other hand, in the general model of the solar system formation, the collisional growth of the dust particles can be expected to produce particles of the meteoroids' size, while the growth rate of the dust particles in the solar nebula depends strongly on the heliocentric distance. For example, Nakagawa et al. (1986) estimated the maximum size of the grown-up dust grains just before the gravitational fragmentation phase based on the Hayashi-model of the proto-solar nebula. They derived 0.6 cm, 5.9 cm, and 19.8 cm at the Neptune, Jupiter, and Earth region, respectively. Although these values depend strongly on which models they use for the proto-solar nebula, the difference of relative size is important. When we assume that the meteoroids are products of the grown-up grains in the proto-solar nebula, the size and the structure of the meteoroids should be different for the birth places of the parent comets, namely the OCs should have larger size meteoroids, while the EKBCs should have smaller.

The trial for detecting larger meteoroids have been performed for recent years by several methods. One is the telescopic search of the scattering light from the large meteoroids in space. Beech et al. (1999, 2004) intensively carried out the survey of large meteoroids along the trail of the Perseid meteor stream by using 1-m class telescope. The other method is to look for the optical flashes caused by the impacts of the larger meteoroids onto the lunar surface. Several impact flashes were detected during the Leonids storm (Ortiz et al., 2000, 2002; Yanagisawa, 2002). Recently, Yanagisawa et al. (private commun. 2004) succeeded to detect the impact flashes caused by the Perseid meteor stream. One of the problems for considering existence of the larger meteoroids is the ejection from the cometary nuclei. The larger, heavier meteoroids may not be able to escape from the nuclei due to the gravitation. Hughes (2000) recently evaluated the maximum size, and concluded that the meteoroids of the order of 50 cm can escape.

The other approach for clarifying the origin may be the researches of the structure of the meteoroids. The evolved structure of the meteoroids at the cometary surface may be dramatically different from that resulted by the collisional evolution in the early solar nebula. It is suggested that, in

some meteor showers, the meteoroids have a weak structure often called as dust-balls, which show frequent fragmentations in the atmosphere. The representative meteor shower is the Giacobinids. Although the velocity of the meteoroids in this meteor shower is low (~ 20 km/s), most of the meteors show the fragmentation during the ablation phase in the atmosphere. The meteoroids in this stream are generally believed to have porous, and weak structure (Beech, 1986). We do not know the reason for the weakness of the meteoroids in the Giacobinids at this stage. One important fact is that the parent comet, 21P/Giacobini-Zinner, is definitely chemically strange object, which shows extremely low abundance of carbon-chain molecules, among the short period comets (A'Hearn et al. 1995). Further study, both in meteors and comets, should be needed to clarify if such structural properties of meteoroids relates to the chemical difference or to the birth place of the parent comets or both. On the other hand, the cluster phenomena observed in the Leonids indicates the fragmentation of the meteoroids during the orbital motion (Watanabe et al., 2003), which should be taken into account if we discuss the evolution of the size distribution of the meteoroids.

5. Concluding Remarks

As described in the first half of this paper, the predictions of the activities of meteor showers are possible to be done with a help of the dust trail theory under the condition in knowing the orbital elements of the parent comets. It is safely to say that this is a new era of the meteor astronomy, and we are able to utilize such prediction for planning observations, which will definitely result in progress of understandings on meteoroids, the structure and the evolution of the meteor streams. In the latter half in this review, the possible new insights on the interrelation between comets and meteoroids are introduced. Most of the indicated facts, such as the dependence of the crystalline to amorphous ratio of the cometary silicate grains on the dynamical class of comets, should be studied further. Although it is difficult at present to distinguish such difference on the meteoroids by the ground-based observations, it may be useful for us to search for any systematic difference of the chemical components or structure of the meteoroids among the different meteor showers, which may be namely different birth place of the parent comets. Such perspective should be important for clarifying not only the origin of the meteoroids, but also the interrelations between comets and meteoroids related to the early history of the solar system.

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METEORIC ACTIVITIES OF THE LAST MILLENNIUM

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Abstract. We have analyzed the meteor records in the chronicles of the east Asian countries, especially the Korean records. Our results show that the seasonal variation of sporadic meteors has persisted at least for the last two millennia. We also observed the prominent showers such as the Perseids and the Leonids, which are formed by Halley-type comets. We obtained the regression rate of nodal points for the Leonids to be approximately 1.52 ± 0.04 days per century.

Keywords: historical meteors, ancient meteor showers, meteoroids

1. Introduction

Meteor streams are formed of meteoroids supplied by comets and asteroids. A meteor shower happens during the Earth's passage into a stream. As time goes by, the stream is dispersed, and these dispersed meteoroids become sporadic meteors. The annual activities of sporadic meteors and meteor showers are observed in detail with modern astronomical techniques. However, their long-term variations can only be investigated with historical records of meteors. We can also investigate the life-time of meteor streams and the orbital changes of their parent comets.

Such historical records of meteors can be found in ancient chronicles around the world, including the Arabian (Rada and Stephenson, 1992), European (Dall'olmo, 1978), Chinese (Beijing Observatory, 1988), Japanese (Kanda, 1935; Ohzaki, 1994), and Korean records (Ahn, 2003, 2004a, b, 2005). Most of the accessible historical sources, especially those of East Asia, have been examined recently. However, there are more things to do, especially when it comes to the Korean sources. Although the number of meteor records in Korean chronicles such as *the Royal Chronicles of the Choson dynasty* (AD 1392–1910) is at least as large as that of Chinese one, the Korean records has yet to be compiled and published.

A typical record of an individual meteor has meaningful information such as appearance date and time, starting and ending points of trail, brightness, color, and occurrence of sound. Inspecting each record, we can see that most of the records were fireballs. This is because only very spectacular event such as fireballs and bolides could attract enough attention to be recorded by the

ancient astronomers. The most direct information in these data must be the appearance date, and so we now concentrate on analyzing them to understand the long-term variations of meteoric activities.

It is well-known from the modern observations (e.g. Yrjölä and Jenniskens, 1998) that the annual activity of sporadic meteors shows a sinusoidal pattern, which is due to the rotating axis of the Earth is inclined by 23.5° with respect to the ecliptic plane. Thus, for northern hemisphere observers, the elevation of the apex of the Earth's way reaches a maximum in autumn, because the ecliptic lies north of the equator at this time. Thus, sporadic meteor activity reaches a maximum near the Autumnal equinox, while a minimum appears near the Vernal equinox. For southern hemisphere observers, the approximate reverse is true.

If we assume that the same is true for the ancient times, historical records can be thought to be randomly sampled from the parent distribution which is similar to that from the modern observations. Then, conceptually thinking, we can reconstruct the parent distribution from the historical records in a Monte Carlo scheme, when the sample size is sufficiently large. We have carried on these researches for a couple of years (Ahn, 2003, 2004a, b, 2005), and will now report some results in this paper.

2. Results

2.1. KORYO (AD 918–1392) AND SONG (AD 960–1275)

The Koryo dynasty was established in AD 918 and perished in AD 1392. The Koryo people preserved their own historical records, which were edited and published into *Koryosa* or *the Chronicles of the Koryo dynasty* in AD 1451 by scholars of the next *Choson* dynasty (AD 1392–1910). The chronicles contain volumes on the astronomical phenomena such as solar and lunar eclipses, occultation of stars and planets by the moon, aurorae, comets, novae and supernovae, and meteors. In *Koryosa*, there are about 730 meteor records in total.

Yrjölä and Jenniskens (1998) showed the total daily mean hourly count of meteors as a function of date in the year of the radio observation. We make a similar plot with the *Koryo* data. In order to avoid the influence of the precession of the Earth on the results, we adopt the number of days within the sidereal year of each record as time coordinate, represented by Λ . We show the results in Figure 1.

We can also find an independent data set in the Chinese chronicles. The Chinese *Song* dynasty (AD 960–1265) was approximately coeval with the *Koryo* dynasty. The meteor records of that period are preserved in *Songshi*, the chronicle of the *Song* dynasty. The number of meteor records is

approximately 1,500, which is twice as large as that in *Koryosa*. We analyze the *Song* data with the similar method to the *Koryo* data. We also show our results in Figure 1.

2.2. THE CHOSON DYNASTY(AD 1392–1910)

The *Koryo* dynasty was followed by the *Choson* dynasty (AD 1392–1910). Its history has been preserved in the *Royal Chronicles of the Choson dynasty* (*Choson–Wangjo–Sillok*) and the *Daily Records of Royal Secretariat of the Choson Dynasty* (*Seungjeongwon–illgy*). The former contains the records between AD 1392 and 1863, while the latter contains those between AD 1623 and 1910. We compiled thoroughly the meteor records in the *Royal chronicle of the Choson dynasty*. However, only records from AD 1623 to 1763 in the *Daily Records of Royal Secretariat of the Choson Dynasty* were compiled, because only those records are digitally available as of October 2004.

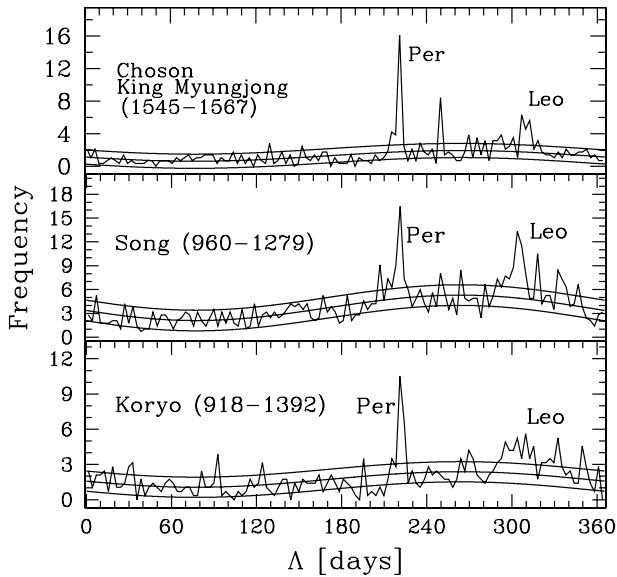


Figure 1. Annual meteoric activities found from historical meteor records written in the chronicles of the Korean *Koryo* dynasty (bottom), the Chinese *Song* dynasty (middle), and the Korean *Choson* dynasty (top). The dashed lines represent the best-fit curve for annual sporadic activity, and the dotted lines represent their 1σ fluctuation. Here *Per* represents the Perseids, and *Leo* means the Leonids. The *Choson* result is made by analyzing data during the reigning period of only one king, *Myungjong*, written in the Royal chronicle of the *Choson* dynasty. Note that there are more than 20 kings, and that the data in the *Daily Records of Royal Secretariat of the Choson Dynasty* are richer and more detailed than those in the *Royal chronicle of the Choson dynasty*.

Although the durations encompassed by the two data sets are very different, the numbers of records are the same, i.e. approximately 3,500.

We inspect the number of records for reigning period of each king, and find the reigning periods having sufficiently large numbers of records. Then, the same analysis method of the previous subsection was applied to those data sets. One of our results are showed in Figure 1. We can see in the figure the same annual sinusoidal pattern of sporadic meteors, and also the conspicuous peaks representing meteor showers. The main two showers, i.e. the Perseids and the Leonids, are seen in the figure.

3. Historical Meteor Showers

We analyzed the individual meteor records preserved in historical chronicles of Korea, Japan, and China for the last millennium. We discovered that the annual sinusoidal pattern of sporadic meteors has existed for the last millennium. Also the two prominent concentrations of meteor records during a year has been discovered, and obviously they were meteor showers. Their

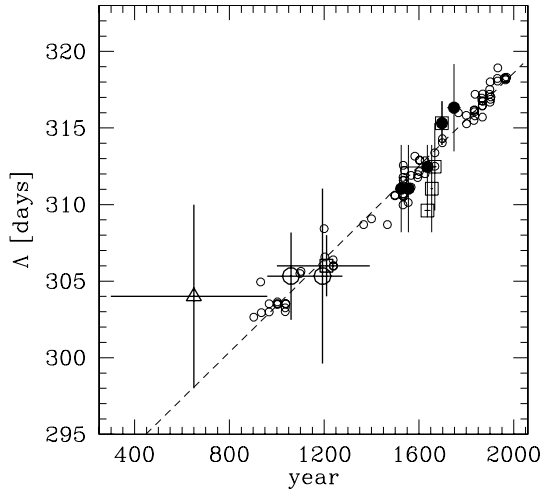


Figure 2. Shift of appearance dates of the Leonid meteor showers. The small open dots are historical meteor showers compiled by Mason in 1995. The large open circles with error bars are showers found from individual meteors of the Northern *Song* and the Southern *Song*. The large open square with error bars represents the Leonids during the *Koryo* dynasty. The large open triangle with error bars represents the shower during the period before the *Song* dynasty. The large solid dots with error bars are showers found from the individual meteor events recorded in the *Royal Chronicles of the Choson dynasty*. The open squares represent showers found from data in the *Daily Records of Royal Secretariat of the Choson Dynasty*.

appearance date indicates that the August shower was the Perseids and that the November shower was the Leonids. The parent bodies of these annual meteor showers are 109P/Swift-Tuttle and 55P/Tempel-Tuttle, respectively. We note that they are short-period comets, especially Halley-type comets. Due to the mean-motion resonance mainly with Jupiter, the large dust grains ejected from these comets produce long-lived, highly concentrated streams of particles located close to the parent cometary orbits (Emel'yanenko, 1984; Emel'yanenko, 1988; Asher et al., 1994, 1999, Jenniskens and Betlem, 2000; Jenniskens et al., 2002). Thus, the ancient meteor showers we found in this paper have persisted for the last millennium.

It is a very well-known fact that the orbit of the parent body of the Leonids has been precessed. We plot the historical records of the Leonid showers and storms in Figure 2, as well as the Leonids found in our work. We make a least-squares fit, obtaining $\Lambda(t) = (288^d.2 \pm 0^d.6) + (1^d.52 \pm 0^d.04)t$, where t is time in centuries. The dashed diagonal line in the figure represents the best fit line for the data. The nodal advancement rate of the meteor stream was also given to be $1^d.457 \pm 0.027$ per century by Toth (1999). The nodal advancement rate of the parent body, 55P/Tempel-Tuttle, was given to be $1^d.475$ per century by Newton (1864).

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A FINE STRUCTURE OF THE PERSEID METEOROID STREAM

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Abstract. A fine structure of the Perseid stream in the range of photographic magnitudes is studied using the method of indices. A new completed 2003 version of the IAU Meteor Data Center Catalogue of 4581 photographic orbits is used. The method of indices is used to acquire a basic data set for the Perseids. Subsequently, the method is applied on the chosen Perseids to study their structure. Sixty four percent of chosen Perseids taken into account are attached to one of the 17 determined filaments of orbits. The filaments are not distributed in the space accidentally, but they form a higher structure consisting of at least four well-defined and distinguished “branches”.

Keywords: Fine structure of Perseids, meteoroids, photographic meteor orbits

1. Input Data and Method Used

A fine structure of the Perseid stream is studied using the method of indices – the procedure based only on mathematical statistics. A new completed 2003 version of the IAU Meteor Data Center Catalogue of 4581 precise photographic orbits (Lindblad et al., 2005) is used. Meteors with heliocentric velocities higher than 48 km/s are rejected from the analysis. Hence, the final set consists of 4526 orbits.

The method was also used in the past to identify the major meteoroid streams in the previous version of the catalogue (Svoreň et al., 2000). In that test run, all the major streams were identified, confirming the efficiency of the procedure. Besides the identification of the streams and associations, the method also enables a study of the fine structure of the streams and their filaments, a separation of which by an iterative method is complicated and hardly applicable. In this paper, the fine structure of the Perseid stream is studied applying the method of indices to the newest version of the photographic orbits database.

A detailed description of the method was published earlier (Svoreň et al., 2000).

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2. Groups of Similar Orbits

In the first step, the method of indices is applied to the whole IAU MDC catalogue to select a basic set of data – Perseids. As a result, in total 875 Perseid orbits are selected from the catalogue.

On the basis of previous results (Svoreň et al., 2000) the individual numbers of intervals were used in the division of each parameter. The divisions were reciprocally proportional to the relative errors of the parameters. The errors of 8 individual parameters are determined as the root-of-mean-squares deviations for the actually chosen 875 Perseids from the mean values.

Table I lists (i) the parameters considered in the method of indices (in headings), (ii) the errors of the parameters for the Perseid stream, (iii) the ranges of the parameters, i.e. the differences between highest and lowest values of selected Perseids, (iv) the ratios of a given range and the corresponding mean error, the result moreover divided by the empirical value (2.04 in our case). This value satisfies a condition that, for all the considered parameters, the sum of squares of differences between real values and the closest integers is minimal. (v) The corresponding nearest integers, serving as a basic set of numbers for the division of the parameters into the equidistant intervals, are written in the last row.

We introduce the term *association* for a group of meteors which consists of at least three similar orbits. For the investigated Perseids, the basic set of parameters (last row of Table I) and its 2-multiple give very similar numbers of associations (53 and 57). We prefer the results obtained by using 2-multiple of the basic numbers with a lower number of members (452 meteor orbits grouped into 57 associations) giving more concentrated associations. The number of orbits in the associations vary between 3 and 79.

TABLE I
The mean errors (MEs) and the numbers of intervals of basic division

Parameter	q	e	ω	Ω	i	α	δ	v_g
ME	0.021	0.14	6.5	4.7	2.6	7.1	1.8	1.8
Range	0.223	1.15	74.9	64.9	23.2	85.0	18.8	15.7
Range/ME/2.04	5.20	4.02	5.65	6.77	4.37	5.87	5.12	4.27
intervals	5	4	6	7	4	6	5	4

Besides the five orbital elements incorporated in the Southworth–Hawkins D -criterion, we also include, in the procedure, the coordinates of the radiant and the geocentric velocity (Svoreň et al., 2000).

3. Structure of the Perseid Meteoroid Stream

A clustering of orbits in the space means a clustering of their orbital parameters. Hence, we deal with the associations of orbits, it holds true for their mean parameters also. In the previous paper concerning the Perseids (Svoren̂ et al., 2001), the meaningful dependences of their mean parameters on each other were searched. We found that the dependences $q = q(e)$, $q = q(\omega)$, and $\omega = \omega(\Omega)$ (Figure 1 as an example) were sufficient to decide if particular associations are components of a given cluster.

A clustering of associations in a single parameter can occur by chance. If a given set of associations really creates a cluster, then the clustering has to be observed in each parameter. Actually, when the above mentioned dependences, with separate clusters, are graphically displayed, it is obvious that the associations tend to be in relatively isolated areas. Almost all the associations detected within a single area on a graph are also detected within single areas on the other graphs.

A filament of the Perseid stream can be characterized by a mean parameter being very close to the border between two intervals of our division. In such a case, the appropriate index corresponds with both the neighbouring intervals, i.e. it is not unique and the filament is split into two associations. Or, it can be split into several associations, if more mean parameters of the filament are close to the appropriate borders of their divisions.

The empirical limits among the filaments, obtained from the graphs (shown only for $\omega = \omega(\Omega)$ in Figure 1 because of the page limit), are listed in Table II.

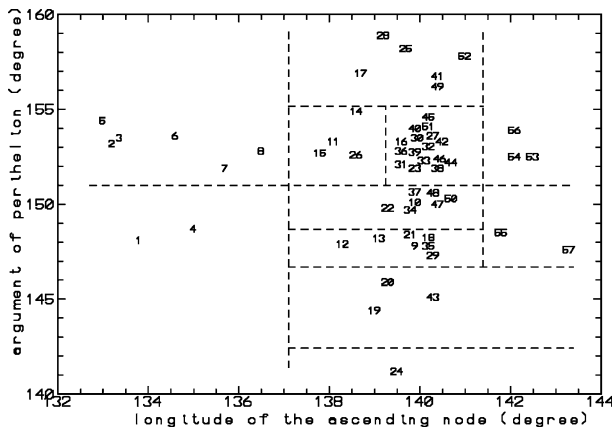


Figure 1. The dependence $\omega = \omega(\Omega)$ for the associations selected. The associations are identified by their serial numbers. The position of assigned numbers (1–57) correspond to the mean values of ω and Ω of respective association.

TABLE II
The empirical limits of parameters q , e , ω , and Ω separating the groups of associations

D.r.	Range	D.r.	Range	D.r.	Range	D.r.	Range
$q1$	0.916–0.926	$e1$	0.712–0.864	$\omega1$	140.5–142.3	$\Omega1$	132.3–137.2
$q2$	0.926–0.942	$e2$	0.864–1.193	$\omega2$	142.3–146.7	$\Omega2$	137.2–139.2
$q3$	0.942–0.950	$e3$	1.193–1.536	$\omega3$	146.7–148.8	$\Omega3$	139.2–141.4
$q4$	0.950–0.965			$\omega4$	148.8–151.0	$\Omega4$	141.4–145.4
$q5$	0.965–0.985			$\omega5$	151.0–155.1		
				$\omega6$	155.1–158.6		

D.r.– designation of range.

TABLE III
The characteristics of the Perseid-stream filaments

D.rs.	Q	N.o.	α	δ	V_g	q	e	ω	Ω	i
$\Omega1, \omega3, q2, e2$	<i>A</i>	15	43.3	57.9	58.70	0.937	0.971	147.7	135.1	111.4
$\Omega1, \omega5, q4, e2$	<i>B</i>	36	39.3	56.8	59.27	0.958	0.981	152.7	134.4	112.5
$\Omega2, \omega2, q1, e2$	<i>C</i>	7	50.0	57.7	58.61	0.921	0.907	143.9	138.9	113.2
$\Omega2, \omega2, q2, e1$	<i>D</i>	8	47.3	57.4	56.56	0.935	0.744	144.9	139.1	111.9
$\Omega2, \omega3, q2, e2$	<i>E</i>	10	48.0	59.2	58.39	0.936	0.959	147.6	138.7	110.7
$\Omega2, \omega5, q4, e2$	<i>F</i>	23	44.3	57.8	59.45	0.959	0.985	153.0	138.3	113.0
$\Omega2, \omega6, q5, e2$	<i>G</i>	10	42.3	57.3	59.35	0.974	0.958	157.0	138.7	113.3
$\Omega3, \omega1, q1, e1$	<i>H</i>	3	49.7	57.7	56.10	0.917	0.722	140.7	139.5	111.5
$\Omega3, \omega2, q2, e1$	<i>I</i>	7	49.7	57.5	57.35	0.931	0.795	144.7	140.1	112.8
$\Omega3, \omega3, q2, e2$	<i>J</i>	53	50.0	57.8	59.05	0.936	0.933	147.5	140.1	113.6
$\Omega3, \omega4, q3, e2$	<i>K</i>	47	48.9	58.0	59.45	0.945	0.975	149.7	140.0	113.4
$\Omega3, \omega4, q4, e1$	<i>L</i>	5	45.9	57.3	57.04	0.956	0.762	150.1	139.9	112.4
$\Omega3, \omega5, q4, e2$	<i>M</i>	242	47.1	57.9	59.32	0.956	0.958	152.2	140.0	113.3
$\Omega3, \omega5, q4, e3$	<i>N</i>	21	48.5	57.5	62.84	0.956	1.214	153.7	140.0	115.8
$\Omega3, \omega6, q5, e2$	<i>O</i>	40	45.1	57.4	60.01	0.971	0.993	156.4	140.2	114.3
$\Omega4, \omega3, q2, e2$	<i>P</i>	17	53.8	58.3	59.07	0.936	0.927	147.4	142.8	113.7
$\Omega4, \omega5, q4, e2$	<i>R</i>	16	50.1	58.3	59.20	0.957	0.939	152.5	142.3	113.5

D.rs. – designation of combination of range, Q – designation of filament, N.o.– number of orbits.

In the next step, the derived limits are used to search in a whole datafile of 875 Perseids, not only among 452 orbits assigned to the 57 associations. A total of 560 (64%) of the Perseid orbits can be assigned to the 17 filaments (*A–R*) listed in Table III. In total, 360 combinations of Ω , ω , q , and e are possible, but only 17 are actually present in the data.

The mean eccentricity of the filament *N* is $\bar{e} > 1$. It is known that many of the Perseids (and equally other streams on retrograde orbits) have formally

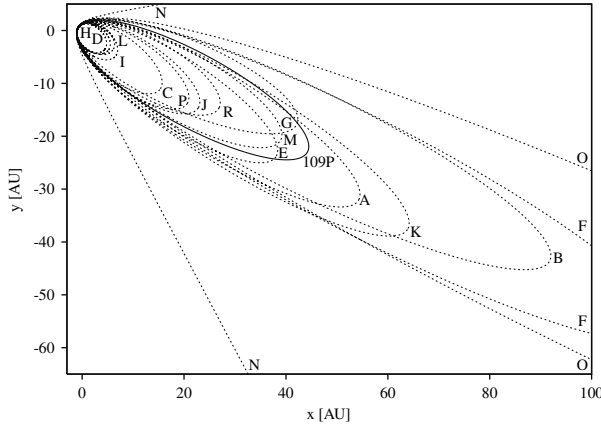


Figure 2. A projection the orbits of filaments into the plane of the mean orbit of 560 Perseids. The orbit of comet 109P/Swift-Tuttle is that in 1862. In the scale of figure, there is no difference between that and 1992 orbits.

hyperbolic orbits (Kresák and Porubčan, 1970). This is an effect of a large uncertainty of this element. Its range, even for mean orbits (high smoothed values), is from 0.722 to 1.214. The high determined values indicate the high real values, but the corresponding real orbits are obviously elliptic.

The selected filaments are, very probably, real structures in the space. To support their real existence we note that each of the derived filaments consists of meteors observed in different years. It also means that the filaments do not represent any clustering of meteoroids in some positions on the orbit but long-time structures of the stream.

4. Filaments as a Part of Complicated Structure – Branches

An analysis of the positions of the selected filaments shows that a part of them is not distributed in the space accidentally, but they form higher structures, called *branches* of the Perseid meteoroid stream.

Different approaches to the analysis can be used. The simplest method is to investigate a dependence of an occurrence of filaments on the time scale represented by a value of orbital ascending node Ω . Or, we can analyze the positions of perihelia of the filaments in the celestial sphere.

Here, we present only an analysis based on a visualization of space distribution of the filaments (Figure 2). We can distinguish following four branches:

- B1 – filaments *H, D, L, I*;
- B2 – filaments *(C), P, J, (R)*;
- B3 – filaments *(G), M, E*;
- B4 – filaments *A, K*.

Four filaments (B , F , O , N) at the “parabolic border” of the eccentricity interval seem to be individual structures without any connection with the other filaments. At branch $B2$, the filament R is relatively distant. Its classification as a part of this branch is questionable. It is possible that the filaments of $B2$ branch represent a transition state between the $B1$ and $B3$ branches.

We have to take into account that our conclusions are considerably influenced by the positions of aphelia closely connected with an eccentricity – parameter with the largest errors in the database. On the other hand, clustering of the aphelia could hardly be connected with a low precision of determination of meteor velocity.

In the last step, D -discriminants among all the pairs of selected filaments are calculated. On the basis of similarity of orbits expressed by the lowest value of D , a check of reality of branches found at previous section is done. The process of the check by D -criterion does not confirm that filament G belongs to the branch $B3$ and filament R tends more to belong to the $B3$ than $B2$ branch. Mean orbits of all the other numbers of branches are very similar to each other (in the range of the individual branch) and a similar dynamical evolution is possible.

5. Conclusions

We have separated and analyzed a set of 875 photographic Perseids. A total of 560 individual orbits are concentrated into 5 individual filaments and 4 branches of the stream containing 12 filaments together. The structures are divided in a cloud of 315 dispersed orbits.

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METEOROID STREAMS ASSOCIATED TO COMETS 9P/TEMPEL 1 AND 67P/CHURYUMOV-GERASIMENKO

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Abstract. The meteoroid streams associated to short-period comets 9P/Tempel 1 (the target of the Deep Impact mission) and 67P/Churyumov-Gerasimenko (the target of the Rosetta mission) are studied. Their structure is overwhelmingly under the control of Jupiter and repeated relatively close encounters cause a reversal of the direction of the spatial distribution of the stream relative to the comet: an initial stream trailing the comet as usually seen eventually collapses, becomes a new stream leading the comet and even splits into several components. Although these two comets do not produce meteor showers on Earth, this above feature shows that meteor storms can occur several years before the perihelion passage of a parent body.

Keywords: meteors, meteoroids, comets: individual: 67P/Churyumov-Gerasimenko, comets: individual: 9P/Tempel 1, celestial mechanics

1. Introduction

The dynamical evolution of meteoroid streams has been studied by many authors (Williams, 1997; Brown and Jones, 1998; McNaught and Asher, 1999; Lyytinen et al., 2001; Vaubaillon, 2002; Vaubaillon and Colas, 2004) in order to predict meteor showers on Earth. The purpose of the present investigation is different as it considers the hazard that could experience a space probe when visiting a comet. We focus our attention on comets 9P/Tempel 1, which will be flybied by the Deep Impact spacecraft in July 2005, and 67P/Churyumov-Gerasimenko, which will be orbited by the Rosetta spacecraft in 2014. Our approach to solve the problem, shortly described hereafter in Section 2, is similar to that of Vaubaillon (2002) and Vaubaillon and Colas (2004), but limited to a qualitative analysis: we do not attempt to calculate the amount of dust present in the streams. We present the results for each comet in Sections 3 and 4.

2. A Summary of the Model

The model describing the formation and temporal evolution of a cometary dust stream is similar to that developed by Vaubaillon (2002); the sunlit hemisphere of a cometary nucleus continuously ejects meteoroids at heliocentric distances $R_h < 3$ AU. The ejection velocity is computed from the work of (Crifo and Rodionov, 1997). The gravitational perturbation of the Sun, eight planets (from Mercury to Neptune) and the Moon are taken into account. The ephemerides of these bodies are provided by JPL planetary theory DE406. Non-gravitational forces such as the radiation pressure as well as the Poynting–Robertson drag are also considered in this approach. The radius of the meteoroids ranges from 0.1 to 10 mm and this interval is divided in five equally-spaced bins; 10^4 particles are considered per bin, making a total of 5×10^4 particles per perihelion return. Our numerical integrations cover 20–30 returns of the comets and have been performed on a massively parallel computer (10–30 processors) at CINES (France).

3. Results: Comet 9P/Tempel 1

The feature of the comet that are necessary to build do the simulations were taken from (Lamy et al., 2001). Its orbital elements are provided in Table I.

Figure 1 shows two different configurations of the meteoroid stream ejected by comet 9P/Tempel 1 during its 1850 return. In 1882 (upper plot), the stream exhibits the usual orientation and trails the comet along its orbit.

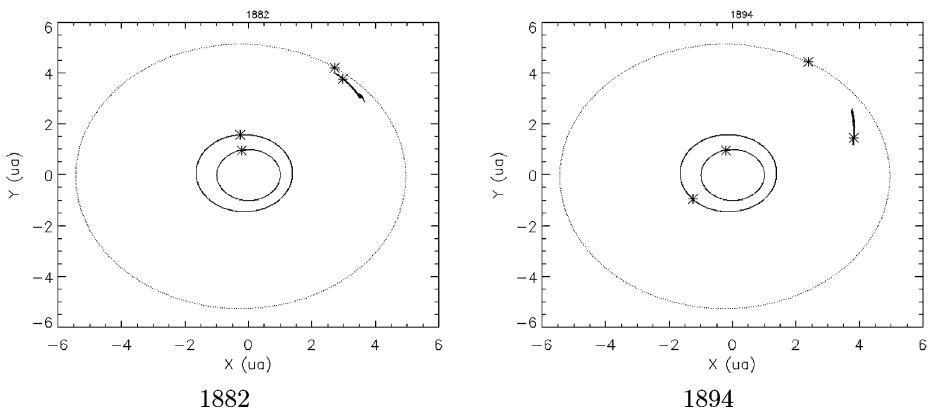


Figure 1. Planar view of two configurations of the meteoroid stream ejected by comet 9P/Tempel 1 at its 1850 return. The coordinates are J2000 rectangular heliocentric and expressed in AU. The three ellipses are the orbits of Earth, Mars and Jupiter, and their location, as well as of the comet, are indicated by the * symbol.

TABLE I
Orbital elements of comet 9P/Tempel 1, for the 2000 perihelion return

Date (Julian Day)	2451545.5
a (AU)	3.1183356706
e	0.518958848
i (°)	10.541361
Ω (°)	68.96652510
ω (°)	178.91152319

In 1894 (lower plot), the opposite situation prevails as the stream is now leading the comet. This results from repeated relatively close encounters with Jupiter at the comet's aphelion (e.g. in 1882, see left panel), which create differences in the semi-major axis, and in turn, in the orbital period of the particles.

4. Results: Comet 67P/Churyumov-Gerasimenko

Comet 67P/Churyumov-Gerasimenko was recently captured in the Jupiter family following a close encounter with this planet in 1959. All physical features of the comet were provided by (Lamy et al., 2003) and (Gutierrez et al., 2003). Its orbital elements are provided in Table II.

Figure 2 shows two different configurations of the meteoroid stream ejected by this comet during its 1938 return. In 1958 (left panel), the stream exhibits the usual orientation and trails the comet along its orbit. In 1974 (right panel), the stream has split into several components following its close encounter with Jupiter in 1959. As in the case of the Pi-Puppis (Vaubailon & Colas, 2004), the encounters took place near the aphelion of the comets where their relative velocity with respect to Jupiter is the smallest. The induced perturbation is then very efficient and, after several revolutions,

Table II
Orbital elements of comet 67P/Churyumov-Gerasimenko, for the 2002 perihelion return

Date (Julian Day)	2452504.5
a (AU)	3.5071390664
e	0.631511923
i (°)	7.120420
Ω (°)	50.96858972
ω (°)	11.45188323

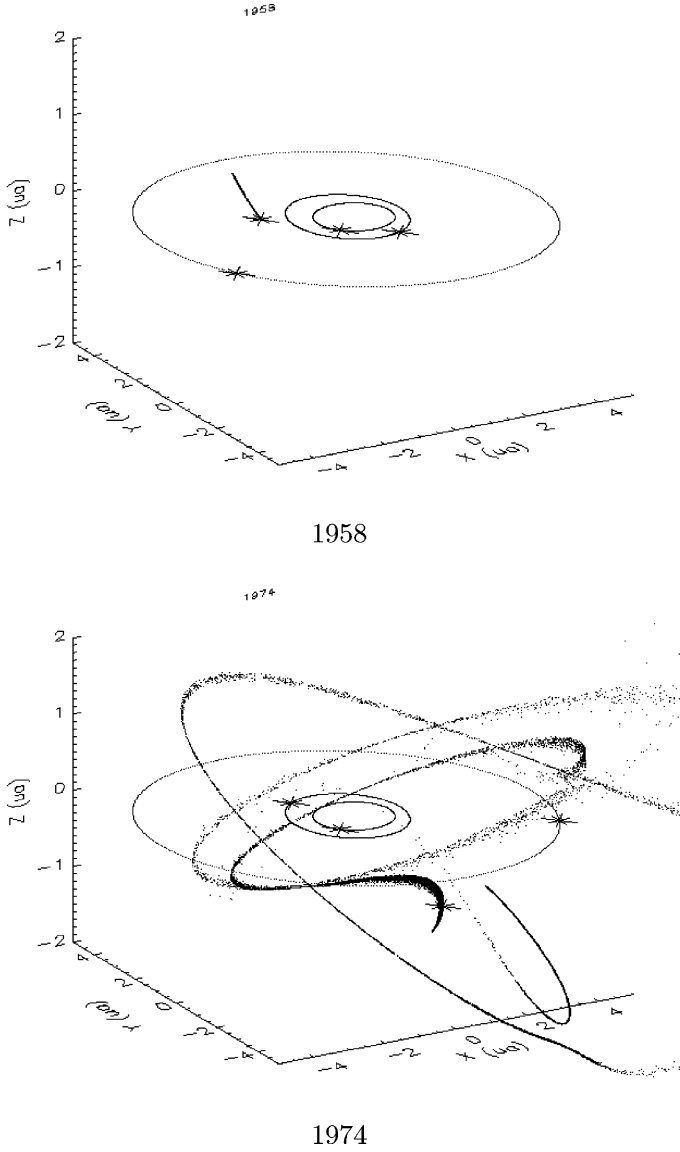


Figure 2. Perspective view of two configurations of the meteoroid stream ejected by comet 67P/Churyumov-Gerasimenko during its 1938 return. See Figure 1 for detail.

the stream separates into several components. Some particles (the furthest to the nucleus) are still on the pre-1959 comet orbit, whereas others (the closest to the nucleus) have orbits similar to the post-1959 comet orbit. Finally, note the large spread of the stream along the Z-axis, again a consequence of the 1959 close encounter.

5. Conclusion

It has already been known that meteor shower enhancements could occur a few years before a comet passage, and this has been interpreted as a consequence of the difference between the orbital period of the comet and that of the stream particles leading the nucleus (Brown and Arlt, 1997; Trigo-Rodríguez, 2002). The process highlighted in this present study is of different nature as stream particles trailing the nucleus can “swing over” under jovian perturbations and later appear as leading the nucleus. Such a reversal in the direction of a meteoroid stream may result in a potential meteor storm on Earth several years before the comet’s return. In addition, this reversal process may temporarily stop the natural spreading of the stream under the combined actions of ejection velocities and gravitational forces and the resulting enhanced density may equally result in a potential meteor storm on Earth. In the ideal case where the reversal process occurs in a plane, the whole stream is confined and the spatial density can then increase by several order of magnitude, compared to a regular stream having the same age (a few revolutions old). Now in reality the process occurs in three dimensions. The enhance of density is thus not as high, but a factor of 10 looks reasonable.

The possible existence of several streams as found in the case of 67P is obviously of major importance for cometary missions. We note that the dust impact experiment on the Stardust spacecraft has detected two well-separated bursts of particles during its flyby of comet 81P/Wild 2 (Economou et al., 2004) and we plan to explore whether this may result from two different streams. A detailed analysis of the case of 67P will be presented in a forthcoming article.

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THE CORE OF THE QUADRANTID METEOROID STREAM IS TWO HUNDRED YEARS OLD

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Abstract. The Quadrantids are one of the most active annual meteor showers and have a number of unusual features. One is a sharp brief maximum, 12–14 h in length. A second is the Quadrantids, relatively recent appearance in our skies, the first observation having likely been made in 1835. Until recently no likely parent with a similar orbit had been observed and previous investigators concluded that the stream was quite old, with the stream's recent appearance and sharp peak attributed to a recent fortuitous convergence of meteoroid orbits. The recent discovery of the near-Earth asteroid 2003 EH1 on an orbit very similar to that of the Quadrantids has almost certainly uncovered the parent body of this stream. From the simulations of the orbit of this body and of meteoroids released at intervals from it in the past, we find that both the sharp peak and recent appearance of the Quadrantids can most easily be explained assuming meteoroids were ejected in substantial numbers near 1800 AD.

Keywords: asteroids, 2003 EH1 – meteors, Quadrantids – meteor showers

1. Introduction

The Quadrantids, which peak in early January, constitute one of the strongest (ZHR $\sim$ 120) meteor showers of the year. It is different from other strong showers like the Perseids, Geminids and Leonids in a number of ways. First, it appeared quite recently in our skies, circa 1800 (Williams et al., 1979) (though the Geminids also turned on in the early 19th century (Rendtel et al., 1995)). Second, it has a very sharp maximum (12–14 h) with extended low-level activity over ± 4 days. The duration of the central portion of the stream implies it is young as noted by Jenniskens et al. (1997), but the weak broader stream has a nodal spread most consistent with a much older age (cf. Jones and Jones, 1993). Third, it has had no known parent body until very recently: Jenniskens (2004) showed that 2003 EH1 is on an orbit very similar to that of the Quadrantid stream. At the high eccentricity and inclination of the Quadrantid orbit, very few of the more than 2000 recently-discovered near-Earth asteroids are present. As a result, it is very unlikely that the similar orbits of the stream and 2003 EH1 are just coincidental given their proximity in phase space. We note that, though the closeness of the orbits implies a

connection between the two, 2003 EH1 hasn't been observed to display cometary activity yet and may be asteroidal.

On the basis of new Quadrantid orbits, Jenniskens et al. (1997) proposed that the stream was much younger (500 years) than previous studies had suggested. Note that this suggestion relates to the stream's narrow core rather than to the broader extent of the stream, which is likely to be much older. More recently, Jenniskens (2004) proposed that, given the proximity of their orbits, the Quadrantids were likely to be a direct recent product of the near-Earth object 2003 EH1, suggesting an age of 500 years based on comparison with earlier models.

2. The Quadrantid Stream and 2003 EH1

Here we propose that the core of the Quadrantid stream is associated with the parent 2003 EH1, but is even younger than has been proposed in the past. We present three lines of argument suggesting that the peak of the stream originated only 200 years ago. First, we show that the location of the observed maximum of the Quadrantids and the point at which 2003 EH1 crosses the ecliptic differ by an amount consistent with 200 years of differential evolution. Second, we integrate thirteen high-accuracy photographic Quadrantid meteor orbits backward along with 2003 EH1 and show that their evolution is consistent with the recent origin we propose here. Third, we simulate hypothetical meteor streams released from 2003 EH1 at various times in the past and show that, for releases prior to 1800, the appearance of the shower in Earth's skies would occur too soon. Taken together, we suggest that these points are most readily explained if the core of the stream is composed of meteoroids released circa 1800, though ejection times as early as 1750 would not be inconsistent with these points generally. We wish to emphasize that the strongest evidence in favour of this interpretation is the lack of Quadrantid observations before about 1830. We note that many other streams of comparable or weaker activity have extensive older records showing clear activity (Perseids, Leonids, cf. Zhuang (1977)) hence this lack of activity is a true feature of the shower.

The overall scenario we propose involves the progressive fragmentation of the original parent body. This process would take several millennia and result in many daughter objects, of which 2003 EH1 is only one. Steel (1991) has put forward a similar hypothesis regarding the Taurid complex. The broad portion of the Quadrantid stream is of order 10^4 yrs old based on its duration, with the central part being much younger due to a release event from 2003 EH1 in circa 1800.

2.1. DIFFERENTIAL EVOLUTION

There have been many observations of the Quadrantid shower since the first recorded instance in 1835 (Quetelet, 1839). Figure 1 is a compilation of reported locations of visual and radar maxima, as far as possible derived from the original sources. Early visual observations have uncertainties that are difficult to quantify, but are important in understanding the regression of the location of this stream, a fact which has been noted by previous authors (Hawkins and Southworth, 1958; Murray, 1982). Observations that do not quote an uncertainty in the peak location are given a value of ± 1 degree in solar longitude here. Given the narrowness of the peak, it is unlikely that any visual observers would have seen the shower had they not observed it relatively close to the maximum.

A weighted least squares fit to the regression rate yields $-0^{\circ}0034 \pm 0^{\circ}0015$ per year. Early studies of observed Quadrantid peak times found somewhat faster precession rates (Hines and Vogan, 1957; Hawkins and Southworth,

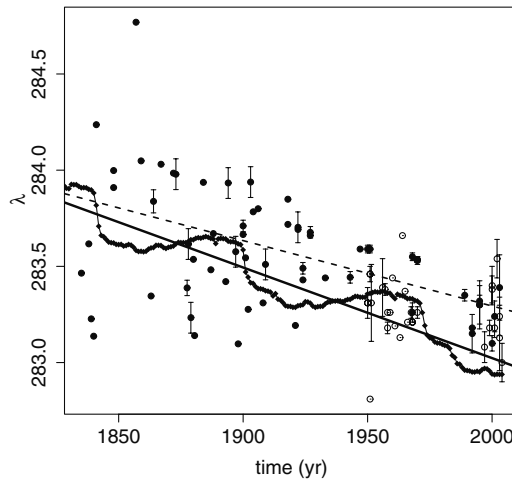


Figure 1. The solar longitude (J2000.0) of the peak of the Quadrantid meteor shower. The solid circles are visual (Quetelet, 1839; Quetelet, 1842; Backhouse, 1884; Denning, 1888; Denning and Wilson, 1918; Denning, 1924; Fisher, 1930; Prentice, 1953; Hindley, 1970; Hindley, 1971; Poole et al., 1972; Roggemans, 1990; Rendtel et al., 1993; Evans and Steele, 1995; Langbroek, 1995; Jenniskens et al., 1997; McBeath, 2000, 2001, 2003; Arlt and Krumov, 2001) determinations, the empty circles are from radar (Hawkins and Almond, 1952; Millman and McKinley, 1953; Bullough, 1954; Hines and Vogan, 1957; Hindley, 1971; Poole et al., 1972; Hughes, 1972; Yellaiah and Lokanadham, 1993; Shimoda and Suzuki, 1995; Brown et al., 1998; McBeath, 1999, 2000, 2001, 2003). The line marked with diamonds marks the longitude of the Sun as seen by 2003 EH1 as it passes close to the Earth's orbit at its descending node (equivalent to the longitude of its ascending node Ω). The heavy line is a linear-least squares fit to the evolution of 2003 EH1; the dashed line is a fit weighted by the uncertainties to the observations. Points without reported uncertainties have no error bars shown, and were assigned uncertainties of ± 1 degree.

1958), but our value is consistent with more recent observational determinations such as that of $-0^{\circ}0038 \pm 0^{\circ}0014$ (Murray, 1982). Fitting a line to 2003 EH1's nodal evolution shows a best-fit slope of $-0.004710 \pm 0^{\circ}000086 \text{ yr}^{-1}$. It is also presently offset from the location of the Quadrantid shower by $\sim 0^{\circ}25$.

Differential precession should cause a separation of this size to arise in $0^{\circ}25/0^{\circ}00131 \text{ yr}^{-1} \approx 200 \text{ yrs}$. These data, particularly the older observations, contain substantial uncertainties. As well, the node of those orbits intersecting the Earth may not be the same as that of the stream as a whole, and some nodal dispersion may be due to the meteoroids' ejection velocities. Nevertheless, this analysis does suggest that the core of the Quadrantid stream was formed only 200 years ago.

2.2. METEOROID ORBITS

A number of high-accuracy photographic orbits of Quadrantids have been obtained by Jacchia and Whipple (1961) and Hawkins and Southworth (1961). By integrating these orbits backward numerically, one can attempt to determine an approximate time of ejection. This was done by computing the proximity of the orbits of the meteors to that of 2003 EH1 (by means of a standard D parameter) as all objects were evolved backward in time (more detail on the algorithm in Section 2.3).

Figure 2 shows the mean values of the D (Southworth and Hawkins, 1963) and D' (Drummond, 1981) parameters of these thirteen meteor orbits

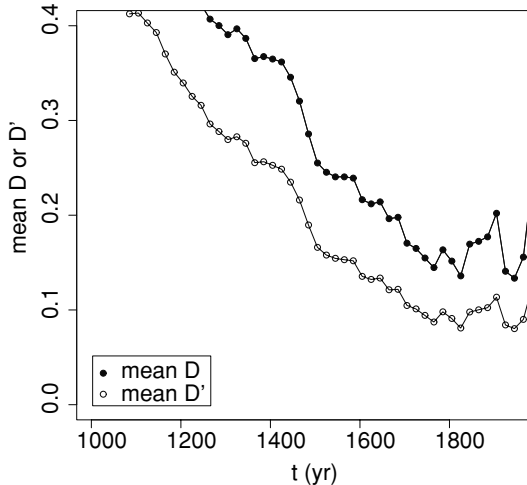


Figure 2. The mean D and D' values of 13 Quadrantid meteors relative to the instantaneous orbit of 2003 EH1 during the recent past.

calculated relative to the instantaneous orbit of 2003 EH1. Both quantities show a marked decrease in the recent past, with minima in the 1800's and a growing separation between the meteoroids and 2003 EH1 in the more distant past. These results must be interpreted with care given the frequent encounters of the bodies with Jupiter, and which results in the magnification of small uncertainties. As a result, we don't expect the simulations to show the meteoroids moving back to their precise launch points from the body in question. Nevertheless, these results suggest that the meteoroids are more likely to have originated from 2003 EH1 recently.

2.3. STREAM MODELLING

The orbit of 2003 EH1, integrated numerically into the past, was used as the starting point for hypothetical meteor streams. An integrator of the Wisdom–Holman type (Wisdom and Holman, 1991) was used for all simulations. The algorithm was modified to handle close approaches symplectically by the hybrid method (Chambers, 1999). A time step of 1 day was used. The eight major planets (except Pluto) are included in all simulations. The asteroids and meteoroids are treated as test particles, in that they feel the planets' influence but not each others.

We investigated the hypothesis that the peak of the Quadrantid stream was released in a single burst at perihelion passage either in 1800 AD (as suggested by the minimum in D' observed in Figure 2, 1600 AD suggested by Jenniskens (2004), or 1491 AD corresponding to the time of perihelion passage of c/1490 Y1, a comet which has been linked to the Quadrantids in the past (Hasegawa, 1979; Williams and Wu, 1993,). The nominal orbit of 2003 EH1, integrated backward, was used as the release point for the simulated meteoroids.

Each outburst was simulated by sixteen sets of 500 particles. Each set had an ejection velocity from the nucleus of 1, 5, 10, 30, 50, 100, 300 or 1000 m/s and β of 0 or 5×10^{-3} . The low (1 and 5 m/s) and high (300 and 1000 m/s) speeds represent the extreme physically probable lower and upper limits for ejection velocities. The ejection directions were chosen randomly over a sphere. The distribution of the resulting orbits, in particular those intersecting the Earth, is compared with observations of the Quadrantid stream. If a meteoroid's nodal distance was found to be within 0.01 AU of the Earth's orbit at a given time, it was considered to become visible as a meteor.

In all three cases the released meteoroids, once integrated forward to the current time, produce meteor showers with orbital elements similar to that of the Quadrantid stream (though with some small number of particles scattered onto quite different orbits). What differentiates most strongly between the different release times is the time of first appearance

in Earth's skies. The 1491 release produces meteors at the Earth prior to 1600, and meteoroids at all release speeds begin to arrive persistently in large numbers by the early 1600's. The 1600 release produces a shower by the late 1600's that is persistent and rising in strength over time. The meteoroids with the smallest release velocities appear last, with those at 5 m/s arriving near 1775, and those at 1 m/s arriving in ~ 1800 . If only very low release velocities are considered, the stream resembles the Quadrantids in orbit and onset time but material released even at 10 m/s arrives in significant numbers by the early 1700's. If the Quadrantid core did arise in 1600 then it must have originated from a very low velocity splitting event, with little of the few tens of meters per second ejection velocities typically expected of cometary out-gassing (Whipple, 1951). The 1800 release scenario produces meteors at the Earth in 20–30 years at all ejection speeds: the flux increases sharply from zero to a strong persistent shower over less than a decade or two. Since the first widely recognized observation of the Quadrantids occurred in 1835 (Quetelet, 1839) this scenario best matches the observed onset of the Quadrantid shower.

3. Conclusions

The sharp core of the Quadrantid stream is most consistent with a recent, relatively short duration release from 2003 EH1, as proposed by Jenniskens (2004). Our studies show that this release event is most likely to have occurred in approximately 1800, for three reasons. First, the separation between the maximum of the Quadrantids and the regression of the node of 2003 EH1 is consistent with 200 years of differential evolution. Second, integrations of high-accuracy meteoroid orbits backward shows minimum D and D' values that better agree with release scenario near 1800. Third, this scenario produces a modelled stream width, orbit, and (most importantly) time of onset completely consistent with the observed Quadrantid stream.

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THE METEOR FLUX: IT DEPENDS HOW YOU LOOK

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Abstract. In this paper, we use radar observations from a 50 MHz radar stationed near Salinas, Puerto Rico, to study the variability of specular as well as non-specular meteor trails in the E-region ionosphere. The observations were made from 18:00 to 08:00 h AST over various days in 1998 and 1999 during the Coqui II Campaign [Urbina et al., 2000, *Geophys. Rev. Lett.* **27**, 2853–2856]. The radar system had two sub-arrays, both produced beams pointed to the north in the magnetic meridian plane, perpendicular to the magnetic field, at an elevation angle of approximately 41 degrees. The Coqui II radar is sensitive to at least two types of echoes from meteor trails: (1) Specular reflections from trails oriented perpendicular to the radar beam, and (2) scattering, or, non-specular reflections, from trails deposited with arbitrary orientations. We examine and compare the diurnal and seasonal variability of echoes from specular and non-specular returns observed with the Coqui II radar. We also compare these results with meteor head echo observations made with the Arecibo 430 MHz radar. We use common region observations of these three types of meteor echoes to show that the diurnal and seasonal variability of specular trails, non-specular trails, and head echoes are not equivalent. The implications of these results on global meteor mass flux estimates obtained from specular meteor observations remains to be examined.

Keywords: Ionospheric radar, Meteors

1. Introduction

Every day billions of meteoroids impact and disintegrate in the Earth's atmosphere. Current estimates for this global meteor flux vary from 2000–200,000 tons per year, and estimates for the average pre-impact speed range

between 10 and 70 km/s (Janches et al., 2000b; Czirzo et al., 2001). Understanding this meteor flux is important for several fields of study from solar system evolution to imaging of gravity waves in mesospheric metal layers (Smith et al., 2000). Yet, the basic properties of this global meteor flux, such as average mass, velocity, and chemical composition remain poorly constrained (Mathews et al., 2001). Additionally, the compositional relationship between optical meteors, meteorites and the source of most of the meteor flux, micro-meteoroids, is only speculative. Many researchers study the physics and chemistry of meteor atmospheric entry and ablation, but require better observational constraints to test their theories (McNeil et al., 2002; Pellinen-Wannberg et al., 2004; Plane 2004]. Finally, several aeronomical phenomena, and their detection, requires meteor flux, such as meteor radar, resonance Lidar, mesospheric airglow, polar mesospheric echoes and noctilucent clouds, and sporadic E, require meteor deposited metals or dust (Kelley and Gelinas, 2000; Smith et al., 2000; Liu et al., 2002; Rapp et al., 2003]. Yet, researchers seldom investigate how the meteor flux might influence these phenomena since this flux is such a complex quantity to estimate precisely. We believe much of the mystery surrounding the basic parameters of the meteor input exists for two reasons. The unknown sampling biases of different meteor observation techniques, and a lack of continuous and routine measurements of radar meteors using advanced techniques. This paper presents a study explicitly demonstrating these biases and the need for further work to understand their source.

For decades, meteor observations were made with cameras and classical meteor radars. Classical meteor radars detect radio waves scattered specularly from the trail of ionization left behind by the meteoroid upon atmospheric entry. The specular condition requires that only trails formed perpendicular to the radar beam axis reflect strongly without destructive interference (Cepelcha et al., 1998). The resulting aeronomical parameters, such as wind and diffusion coefficients, are therefore averages of the trail properties with the first Fresnel zone.

Over the past decade, two new types of radar meteor reflections have been widely observed and studied. These reflections are known as meteor head and non-specular trail echoes and were, until recently, observed with radars designed for incoherent scattering studies of the ionosphere. Examples of these two scattering mechanisms are shown in Figure 1. The radar signature from meteor entry is known as a head echo. Head echoes are often followed by trail reflections, called non-specular trails, which occur despite the fact that many trails are roughly aligned with the radar beam. Non-specular trail echoes are attributed to coherent radio scatter from plasma turbulence-generated field aligned irregularities (FAI) in electron density (shown to the right in Figure 1). Figure 2 show examples of head echoes and non-specular trails from Jicamarca. From this figure, it can be deduced that meteors are

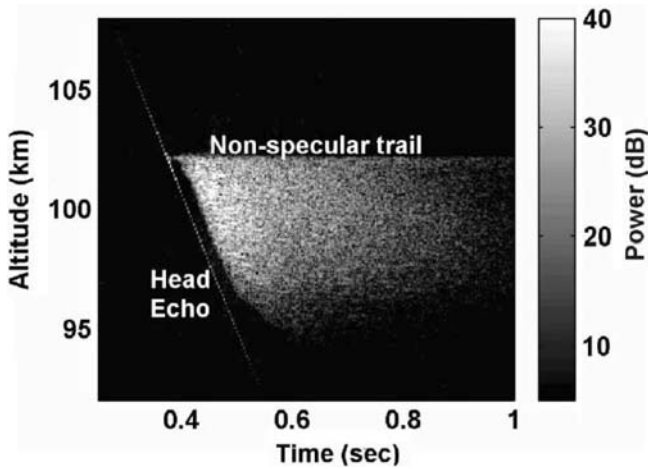


Figure 1. Altitude-time-intensity image of a head and subsequent non-specular echoes over extended range from ALTAIR VHF Radar. The diagonal line to the left is called a head echo, while the echoes spread in range and time to the right are the non-specular trail. Figure reproduced from Close et al. (2002).

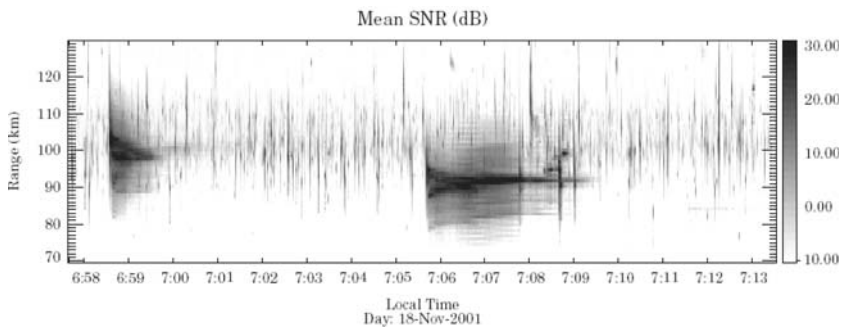


Figure 2. Examples of meteor head echoes and non-specular trails from the Jicamarca 50 MHz Radar, Reproduced from Chau and Woodman (2004).

about the most common coherent reflection that this radar observes. Because these observations produce such detailed signatures, they show great promise as tools for deriving more complex parameters about meteors and the atmosphere they ablate in. In the mean time however, we need to understand how these radar reflections are influenced by different meteor properties such as size and velocity.

This study specifically demonstrates that a 50 MHz radar, operating at moderate power provides detailed meteor observations of non-specular trails, specular trails, and likely head echoes. While studies and detailed analysis has been made on the observation response function of specular meteor trails, little work has been done to compare these observation biases between the

three types of radar reflection (Cervera and Elford, 2004). Perhaps most importantly, this study demonstrates the need for further research into the scattering properties of meteor reflections. By comparing data from these “new” meteor reflections with traditional specular echoes our studies illustrate that each type of reflection is biased towards certain meteor properties, such as size and speed. They also demonstrate the need for a radar system that takes continuous observations of all types of meteor reflections. Doing so will allow us to better understand the meteor flux, its effect on the upper atmosphere.

2. Meteor Observations from the Coqui II Campaign

Traditional meteor radars are low power transmitting only a few kilowatts of power, often in an “all-sky” mode, resulting in low sensitivity. In the past 10 years, high-power, large-aperture (HPLA) radars, operating at powers in the megawatt range have been applied to detecting meteors as well (Lars P. Dyrud, submitted; Janches et al., 2000a, b, 2003; Dyrud et al., 2002, 2004). The difference is that the traditional meteor radars, because of their low power, only see the strong reflections from specular trails, unlike HPLA radars, which also observe specular trails, but more frequently observe meteors via head echoes and non-specular trails. These reflections are thought to be 10–20 dB weaker than specular reflections, but their detection seems independent of the the angle between the radar beam and the trajectory of the meteoroid (Dyrud et al., 2002). We show here that radars transmitting only medium power, 100 kW, with a larger collection area can easily observe the traditional specular meteor trail reflections, but have sufficient sensitivity for frequent non-specular trail observations. Unfortunately, the time resolution of the data available here is insufficient to conclusively distinguish separate head echo observations from the non-specular trails, but we believe that with high enough temporal and spatial resolution, head echoes could be observed with this type of radar as well.

This paper preliminarily investigates the following question: which part of the full spectrum of meteor sizes and speeds do the various radar techniques observe? Information regarding this question undeniable lies in the natural changes in meteor flux that would occur at different local times and different seasons. Taking advantage of the ability of medium powered radars to observe both specular and non-specular meteor trail reflections, we used observations from the Univeristy of Illinois (U of I) radar during the Coqui II campaign in Puerto Rico to explore the diurnal variability between these two types of reflection mechanisms. We show here that the measured diurnal variation in meteor rates are not the same from radar to radar or even between different reflection mechanisms from the same radar. Further examination reveals more similar, but not identical seasonal trends in all

types of reflections. First, we discuss the nature of non-specular reflections as observed by a 50 MHz radar in Puerto Rico, the Coqui II radar deployed in support of the rocket campaign by the same name. The radar was constructed from 8–20 CoCo array elements, operating at moderate peak power (~ 30 kW) (See Urbina et al., 2000 regarding information on this campaign and radar system). Figure 3 is an example of the observations used and shows 20 min of the Coqui II data. This figure reveals that meteor echoes are by far the dominant source of coherent reflections, and examples of both specular and non-specular trails are marked by arrows. We distinguished between the two types of reflection mechanisms using these simple criteria; that a specular reflection must only be 1–2 range bins and have a duration of only one time bin which was 2.5 s for the data used in this study. These criteria are based on the fact that specular trails will occupy only a small altitude range, due to the meteor's orientation with respect to the radar beam. In addition, the instabilities that arise in the non-specular trails are less apparent in specular trails, so their reflections are short-lived and usually less than 1 s. The rest of the meteor reflections were considered non-specular trails.

The following sections present some of the analysis and results of the meteor observations, including the effect of the geomagnetic field on both specular and non-specular trails, and seasonal and diurnal variabilities of all types of reflections.

2.1. THE ROLE OF THE GEOMAGNETIC FIELD IN METEOR DETECTION

On the night of April 3, 1998, the two arrays of the Coqui II radar were split, with one directed off perpendicular to $\mathbf{B}$ and the other directed perpendicular

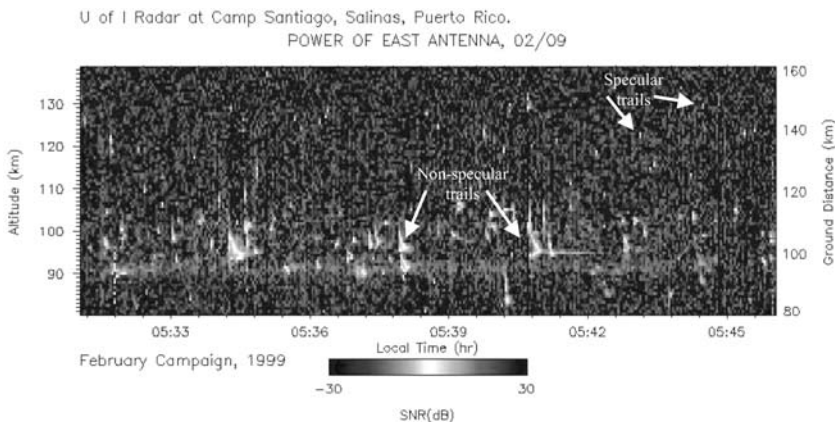


Figure 3. RTI of 20 min of Coqui II data, showing examples of specular trails and non-specular trails.

to **B**. This allowed for the first, simultaneous observations of meteors with radar beams pointed in the $\perp \mathbf{B}$, and off **B** directions. Figure 4 diagrams the orientation of the two beams with respect to the geomagnetic field. This examination extends the results by Zhou et al. (2001) who pointed the MU radar $\perp \mathbf{B}$, off **B**, and $\parallel \mathbf{B}$ to show that every head echo observed $\perp \mathbf{B}$ was accompanied by a non-specular trail, and many non-specular trails were seen without head echoes, but when pointed off **B** no head echoes were seen. Both the results presented by Zhou et al. (2001) and the results presented in the next paragraph indicate that non-specular trails are the result of FAI. However, the Coqui II data are the first simultaneous measurements of this kind, and are useful for these reasons. Simultaneous two beam observations eliminate the effects that otherwise arise due to taking observations at different times, and since time variations do not exist, local time variabilities in trail types can be examined.

Figure 5 shows a histogram of occurrence of both specular and non-specular meteor trails from the beam pointing $\perp \mathbf{B}$. Although there are many more specular reflections than non-specular, some extended in range reflections were observed. Note also that the data for this night only extends from 18:00 through the 01:00 h AST, so the overall diurnal trend cannot be shown on this day. The important conclusion, however, comes from comparing the data from these results to those obtained from the beam pointed off $\perp \mathbf{B}$ which are shown in Figure 6. The comparison reveals two interesting points. (1) Surprisingly, there are fewer occurrences of specular trails than in the off $\perp \mathbf{B}$ direction. This is a new and unreported finding that should be looked into further, but indicates that the magnetic field may play a role in the observation of specular trails as well. (2) Non-specular echoes, conversely, have a dramatic dependence on beam direction, yet, there were a few range spread reflections seen in the off $\perp \mathbf{B}$ direction. However, many of these observed range spread reflections have very high apparent altitudes, much higher than 105 km altitude predicted by ? as the approximate upper limit for the instabilities that lead to non-specular trail reflections. There are two possible explanations of these events: the off $\perp \mathbf{B}$ non-specular trails were

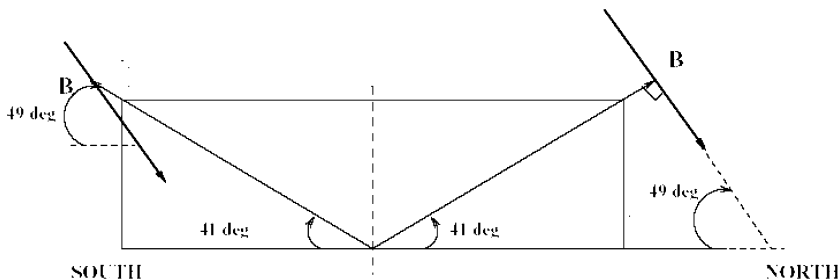


Figure 4. Radar direction on April 3.

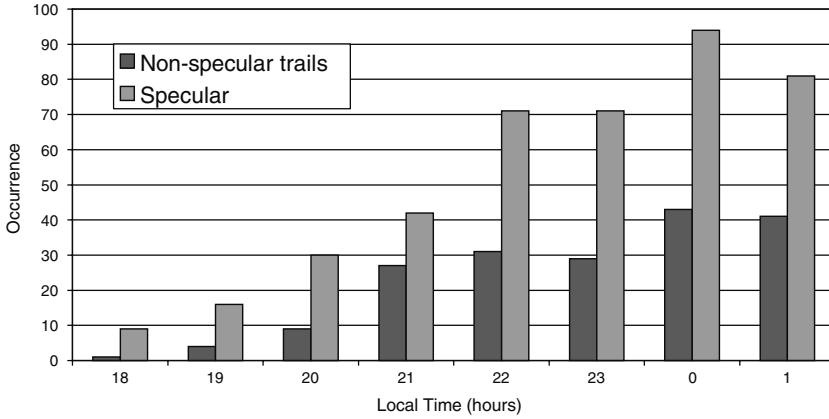


Figure 5. Occurrence rate of specular and non-specular trails when the Coqui II radar pointed perpendicular to **B** (North).

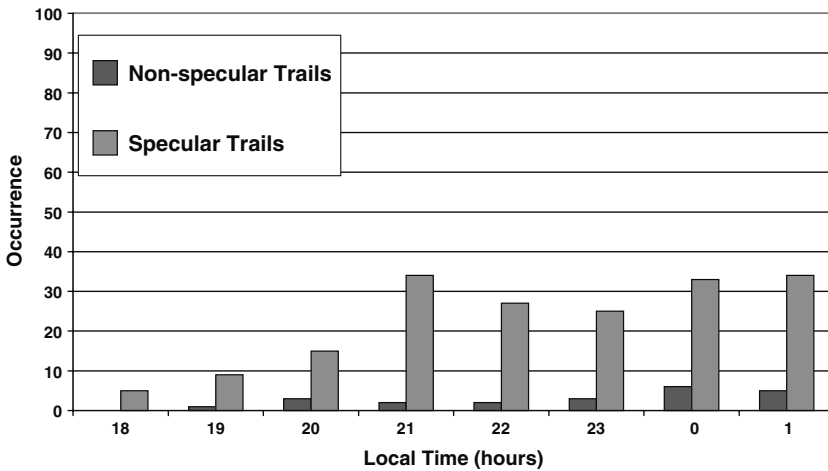


Figure 6. Occurrence rate of specular and non-specular trails when the Coqui II radar pointed off perpendicular to **B** (South).

actually observed in the radar's side lobes, thus giving the effect of a higher altitude detection, or they are actually head echo observations. We believe it is very likely that this system observes some head echoes, because most of these off $\perp \mathbf{B}$ and high altitude detections are spread in range but are shorter in duration than the 2.5 s time bin, which most of the other non-specular trails are not. This provides yet more motivation for a new continuously operating system with high time resolution that is capable of discerning and even studying head echoes. These findings agree with the assertions of Zhou

et al. (2001) and Dyrud et al. (2002), that non-specular trail reflections result from meteor generated FAI, and also show that the magnetic field may influence the detection of specular echoes.

2.2. DIURNAL VARIABILITY IN METEOR OCCURRENCE

We looked in detail at 10 nights of observations spread throughout the year, and counted and binned by time, the occurrences of both specular and non-specular meteor trail reflections. Figure 7 plots occurrence of meteor trail reflections against Puerto Rico local time (AST) for these 10 days of observations. Notice that the evening starts out with more occurrences of specular trail reflections, yet in the morning hours the more frequently observed trail type are non-specular. Furthermore, the peak occurrence of specular trails occurs earlier in the morning, around 03:00 LT, than that for non-specular trails, which peaks at 06:00 LT or later. Unfortunately, our observations end before a clear decrease in non-specular trails can be delineated. This information shows the need for more observations of meteor trails using this type of radar and that extend further into the morning hours. Zhou et al. (2001) for example, also found peaks during the dawn hours of the morning, and in one set of observations, the most non-specular trails occurred between 07:00 and 08:30 AST.

A revealing observation comes from comparing the minimum occurrences in the evenings to maximum number of events in the mornings between the two types of reflection mechanisms. Such a comparison reveals differences in meteor rates due to the 30 km/s orbital velocity of Earth. The

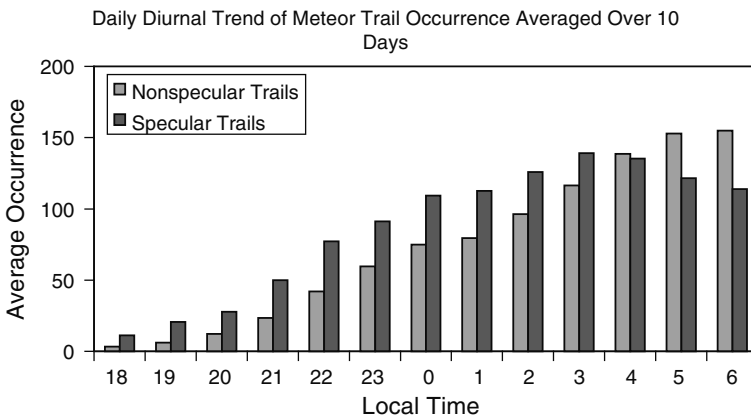


Figure 7. Occurrence rate of non-specular and specular trails over 10 days throughout the year.

results show on average, non-specular trails have an occurrence increase of three times that observed for specular trails during a given diurnal cycle. In summary, specular meteor trails have an max/min ratio in diurnal occurrence of about 8, non-specular trails from the same radar and observing volume have an max/min ratio of about 30, while Figure 9 shows head echoes from the Arecibo UHF (430 MHz) dish occur about several hundred times more frequently at dawn than dusk. We note that Arecibo detects a flux that is formed by particle of smaller size than those detected by traditional meteor radars. These results would indicate that different reflection mechanisms are sensitive to different portions of the meteor flux, because the average meteor velocity impinging on Earth will be 30 km/s faster at dawn than dusk to Earth's orbital velocity. Further, studies using only one radar or relying on one reflection mechanisms will not examine the total picture of incoming meteor flux and will therefore lead to incomplete or perhaps erroneous results regarding the nature and the variability of the sporadic meteor at Earth. Some may point out that the comparatively narrow beam of the Coqui II radar, when combined with the specular condition will cause geometrical effects that will likely effect the diurnal occurrence rate. This, however, does not seem to be the cause of the approximately 8 max/min ratio. Figure 8 shows the diurnal occurrence from an "all-sky" meteor radar from Maui, HI (a similar latitude to Puerto Rico) showing the same factor of 8 max/min ratio. It seems likely that the specular condition is somehow responsible for this factor of 8, and not the observing geometry of the radar. What might cause the profound differences in diurnal variability between the three reflection mechanisms? While we do not yet have answer to this question, we believe the solution lies in how we can understand the "filters" that reflection mechanisms and different radars place on the incoming meteor flux. We believe this study demonstrates a clear unaddressed need for further research.

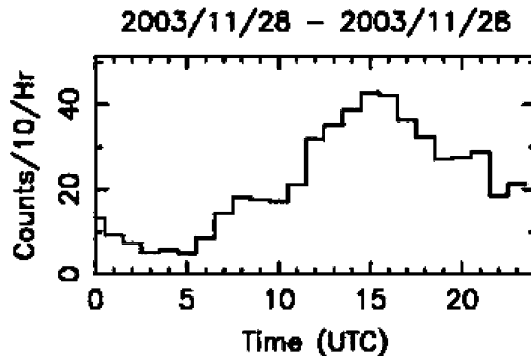


Figure 8. Occurrence of specular echoes over Maui, using an allsky meteor radar (Plot Courtesy of Steve Franke, University of Illinois). Local time is UTC -10.

2.3. SEASONAL VARIATIONS IN METEOR TRAIL OCCURRENCE

We have shown that observing the incoming meteor flux using each head echoes, specular and non-specular trails all produce quite different diurnal variations in occurrence. This section examines seasonal occurrence to show that similar, but differing trends are seen in all types of reflections. Janches et al. (submitted to JASTP) using the Arecibo radar, determined that the number of head echo occurrences per minute varied depending on the month. Figure 9 shows that the head echo occurrence rate is highest in January, and then decreasing in June, then February, and finally lowest in March. The authors note that this effect is due to the variation of the elevation of the Apex point along the year. They also suggest that the maximum flux should be detected in September when the Apex is highest in the local Arecibo sky. Using the the Coqui II database, we can examine if such trends are seen in the meteor flux over Puerto Rico from specular and non-specular reflections. While this data contains some gaps in comparison to Janches et al., we have data from June, March, and February. Figure 10 plots occurrence rates over the 12-h observing period from both non-specular and specular trails. A number of scientific points can be gathered from this graph. First, non-specular trails, which are similar to head echoes in the sense that trails of any

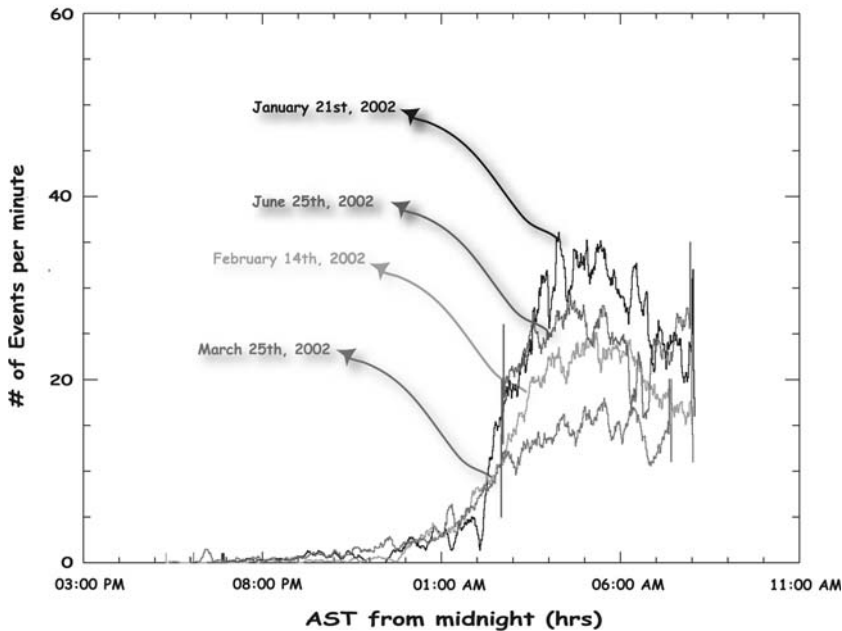


Figure 9. Occurrence of meteor head echoes versus local time, obtained with the Arecibo UHF radar.

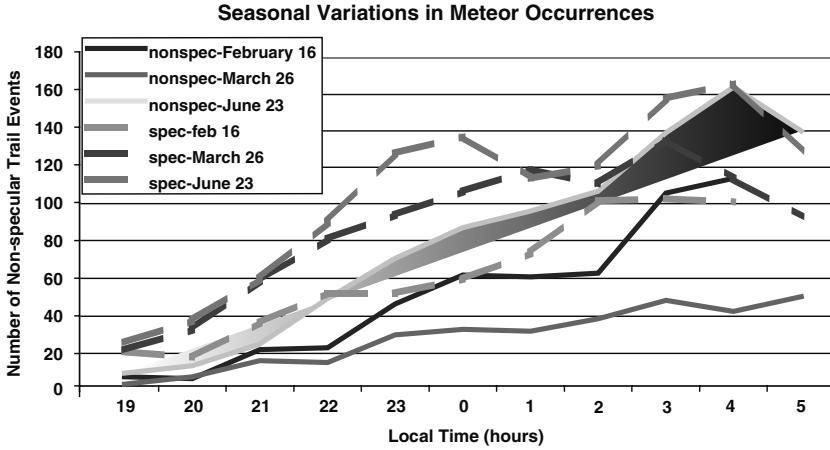


Figure 10. Seasonal variation of both specular and non-specular meteor trails.

angle can be reflected within the observing volume, generally show the same seasonal trend in occurrence. However, specular trails seen by the Coqui II radar have a much weaker seasonal dependence, but still show peak occurrence in June but the minimum occurs in February not March.

One aspect of the seasonal differences is again the overall ratio between minimum and maximum occurrence rates. Looking at the count rates for non-specular trails between 2 and 4 LT yields a factor of 6 between maximum at June and the minimum at March. With specular trails the max/min at the same times is near 3. For head echoes from Arecibo the June/March occurrence ratio is the least, about 2. Without speculating on the causes of the differences and similarities, it is again clear that each reflection mechanism yields different variabilities. The differences between reflection mechanisms currently have no explanation and provide clear evidence that are current understanding of the meteor flux and observations with radar leave a tremendous amount of open questions.

3. Summary

This paper presented the first comparison of meteor occurrence statistics for the three main types of radar meteor reflections. Specular and non-specular observations by a 50 MHz coherent radar in Puerto-Rico were compared with head echo observations made by the Arecibo radar. These comparisons showed clear differences in diurnal and seasonal variability between these three types of meteor reflections. We believe these differences are due to the “filters” that reflection mechanisms and different radars place on the incoming meteor flux. Plenty of speculation is available for understanding

these observation differences between reflection mechanisms, but we currently have no concrete explanation. This paper provide evidence that further research is necessary before radars may be reliably used for studies on the *total* global meteor flux.

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LATITUDINAL VARIATIONS OF DIURNAL METEOR RATES

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Abstract. The presence of a diurnal variation in meteor activity is well established. The sporadic meteor count rates are higher on the local dawn side and lower on the local dusk side. This phenomenon is caused by the Earth's orbital motion and rotation. Meteor radar measurements have been compared from Esrange, Kiruna, Sweden, at 68° N, from Juliusruh, Germany, at 55° N, and from Ascension Island, at 8° S, to investigate how the diurnal variation depends on season at different latitudes. Data have been used from vernal and autumnal equinoxes and summer and winter solstices to locate the largest seasonal differences.

Keywords: Diurnal rate, latitudinal variation, meteor, meteor radar, NEP

1. Introduction

The goal of this study is to investigate diurnal meteor rate differences at different latitudes. The diurnal meteor event rate is expected to differ between latitudes, with a larger seasonal variation at higher latitudes because of the tilt of the Earth's axis (Ceplecha et al., 1998). Meteor radar data from high, mid and equatorial latitudes have been compared.

Being located just north of the Arctic Circle, the Esrange meteor radar provides an interesting viewing geometry. The antenna points almost towards the North Ecliptic Pole (NEP), and hence in the same direction, once every day. The meteor rate in this measurement configuration is also discussed.

2. Radar Parameters, Sites and Observations

The data used for this study was recorded by a SKiYMet all-sky interferometric meteor radar at each site. Electromagnetic pulses are radiated at a high pulse repetition frequency by the transmitter. After reflection on ionization trails of incident meteoroids, the echo is received by an array of five receiver antennas acting as an interferometer. We should note that detection only occurs for meteor trails perpendicular to the radar beam direction. For a complete description of SKiYMet meteor radars see Hocking et al. (2001).

Meteor radar data from high, mid and equatorial latitudes have been used, Esrange at 67.9° N, 21.1° E, Juliusruh at 54.6° N, 13.4° E, and Ascension Island at 8.0° S, 14.4° W, respectively. The Esrange and Ascension Island meteor radars operate at a frequency of 32.50 MHz in the 70–110 km height range. The corresponding figures for the Juliusruh radar are 32.55 MHz and 78–120 km. This radar was transferred to Andøya, Norway, in September 2001.

Data analyzed is from August 1999 to March 2004 for Esrange, from November 1999 to August 2001 for Juliusruh and from May 2001 to November 2003 for Ascension Island. We have chosen 5 days of data around each vernal/autumnal equinox and summer/winter solstice for all three meteor radars. The naming of the seasons applies to the northern hemisphere throughout the paper. Rejecting ambiguities, the mean diurnal meteor rate was calculated. The data sometimes contains many detections from the same meteor trail. Calculations of the time difference between consecutive meteor registrations show a large overweight on times between zero and 0.1 s and many of these detections have practically identical zenith and azimuth angles. Thus, we have defined ambiguous meteor registrations as those detected less than 0.1 s apart and have both azimuth and zenith angles within two degrees from each other. About 85% of these detections have indistinguishable time stamps. The method we have used to determine the sporadic meteor sources visible to the radars is described in Morton and Jones (1982).

3. Seasonal and Latitudinal Variations

The existence of a diurnal variation in meteor rates has already been described by Lovell (1954).

The seasonal diurnal meteor event rate variations at the three radar sites are shown in Figure 1. The shape of the diurnal meteor rate at equatorial latitudes is fairly constant throughout the Earth's orbit. At high latitudes, however, the 23.5° tilt of the Earth's axis makes the radar tilt towards or away from the sporadic meteor sources. The higher the latitude, the larger the effect. The characteristics of the sporadic meteor sources are described in,

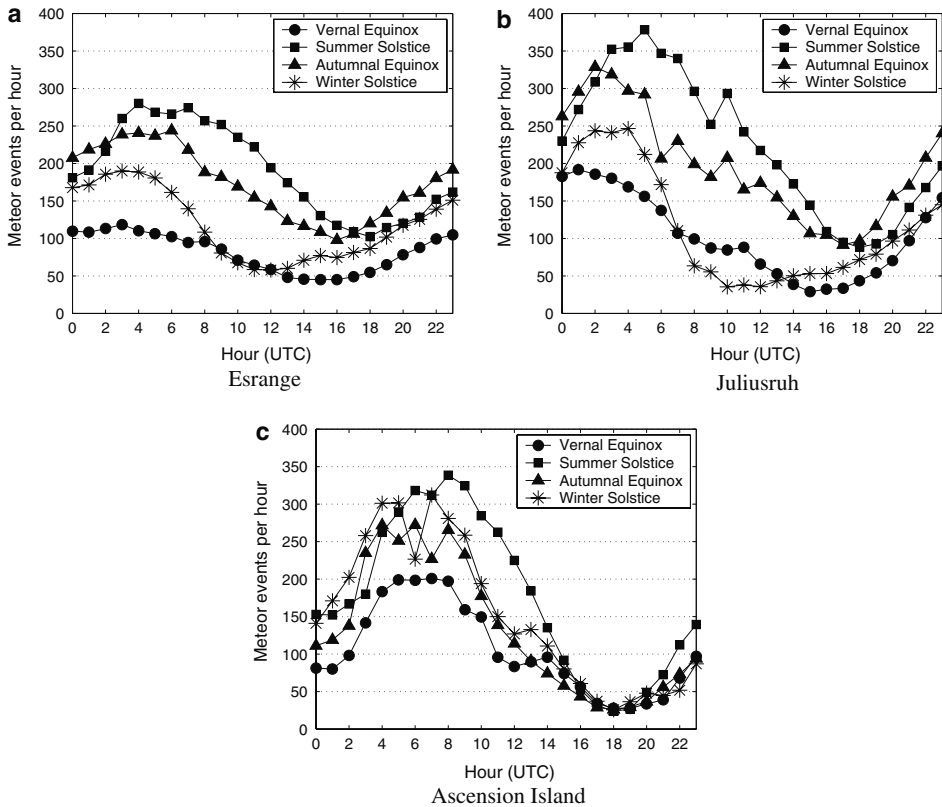


Figure 1. Average vernal/autumnal equinox and summer/winter solstice diurnal rate over all data available for (a) Esrange, (b) Juliusruh and (c) Ascension Island.

e.g., Jones and Brown (1993). A similar study on the diurnal and seasonal variability of the meteoric flux has also been conducted at the South Pole (Janches et al., 2004).

The vernal equinox diurnal meteor event rate at Esrange is very low at all hours and the rate fluctuation has small amplitude (Figure 1a). The meteor radar at Juliusruh also shows a low diurnal event rate at vernal equinox, Figure 1b, but higher amplitude than at Esrange. Figure 1c shows the diurnal rate on Ascension Island. The vernal equinox diurnal rate curve has lower amplitude than the other three curves, which have comparable amplitudes. This implies that the meteoroid distribution is not homogeneous. It appears to be less dense in the first half of the year, which has been pointed out by, e.g., Lovell (1954).

At summer solstice the diurnal rates at both Esrange and Juliusruh have higher amplitudes than at vernal equinox. Compared to the winter solstice rates, the rates are higher at summer solstice.

Figure 1a shows that the meteor rate at autumnal equinox at Esrang is high at all hours. The same is true for Juliusruh, but there the fluctuation amplitude is higher (Figure 1b).

The plots in Figure 2a–d are ordered by season. Figure 2a shows the vernal equinox meteor rate curves for all three radars, Figure 2b shows the summer solstice curves, Figure 2c the autumnal equinox curves and Figure 2d the winter solstice curves. The meteor rate at Esrang seems to have the lowest amplitude. At the same time as the maximum flux is the lowest at Esrang, the minimum flux is the highest at the same latitude.

The interferometric properties of the meteor radars have been used to visualize the sporadic meteor sources. Since the diurnal variation in meteor flux differs between latitudes and also seasons, we do not expect that the sources seen by the three radars are identical. The visibility of different sources also varies during the day, but only the seasonal differences are discussed here.

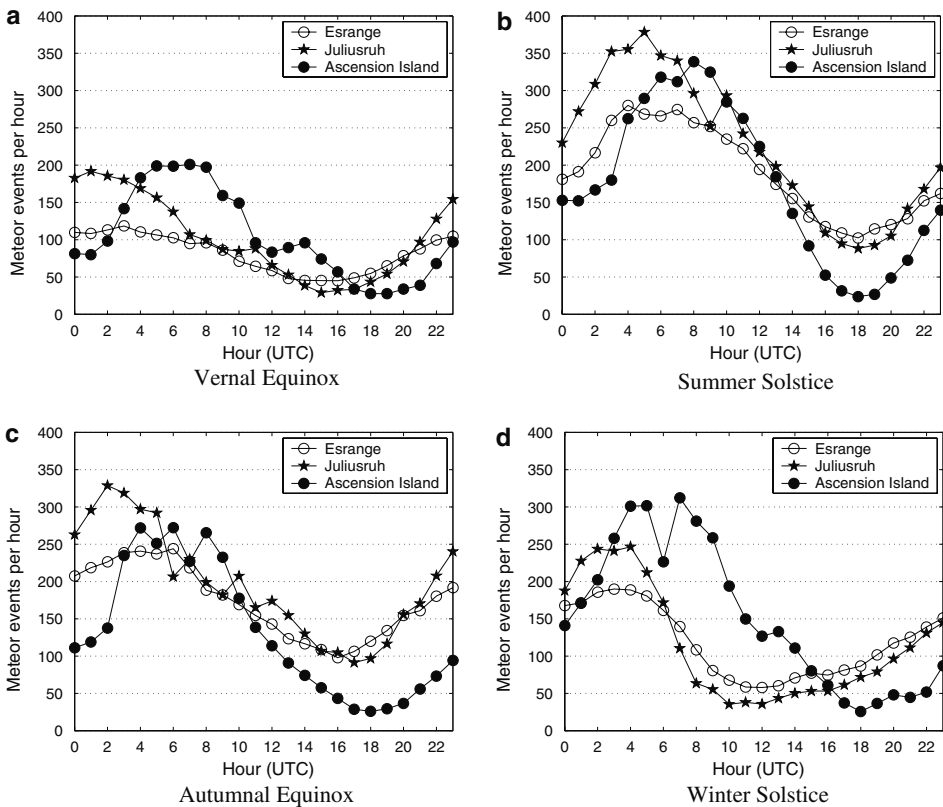


Figure 2. Diurnal meteor event rate at (a) vernal equinox, (b) summer solstice, (c) autumnal equinox and (d) winter solstice at different latitudes.

At vernal equinox the north pole of the Earth's axis is tilted opposite to the motion of the Earth. The sources seen by the Esmare meteor radar are mainly the north toroidal one, while the meteors detected at Juliusruh primarily come from the antihelion. Ascension Island sees a greater variety of sources, namely the helion (highest rate), the south apex, the antihelion and the south toroidal (lowest rate). The north toroidal can also be seen indistinctly.

At summer solstice, when the Earth's axis is tilted towards the Sun, all three meteor radars show similar source distributions. All radars show a high meteor rate at about the helion source, the peak being broadened towards the radiant of the Arietid shower, 7° N ecliptic latitude and 330° sun-centered longitude. No other sources can be seen in Esmare or in Juliusruh data, but Ascension Island data also show the antihelion source.

At autumnal equinox the direction of the tilt of the Earth's axis is opposite to the vernal equinox; the axis is tilted towards the motion of the Earth. The source distribution is different from the previously described ones in the sense that the Esmare meteor radar now sees the north apex as the strongest source, but the helion source is also visible. The strongest of the sources at mid-latitude is the antihelion one, but both the (north) apex and the helion sources are clearly distinguishable. The Ascension Island meteor radar sees primarily helion source meteors, but the detections also contain apex and antihelion meteors and some south toroidal ones.

At winter solstice, the Earth's axis is directed away from the Sun. The strongest source seen with the Esmare meteor radar seems to be the antihelion, but the north apex is also present. The Geminid meteor shower is also discernable at 12° N ecliptic latitude and 210° sun-centered longitude. The Geminids are also distinguishable in the Juliusruh data, which are quite similar to the Esmare data with the antihelion and north apex as the visible sources. The Geminids are only vaguely distinguishable at Ascension Island; the dominating sources are the north and south apex, the helion and the antihelion.

4. North Ecliptic Pole Geometry

Being located less than two degrees north of the Arctic Circle, the Esmare meteor radar points almost towards the NEP once every day. Hence, in this particular position the antenna always points perpendicular to the ecliptic plane. It should therefore picture the northern hemisphere meteoroid flux around the Earth's orbit as the source configuration is identical with respect to the radar. A similar study was done by Singer et al. (2004) for the Andøya meteor radar in Norway.

Taking the meteor flux for the hour closest to the NEP passage each day, Figure 3 shows the monthly average meteor rate for August 1999 to March

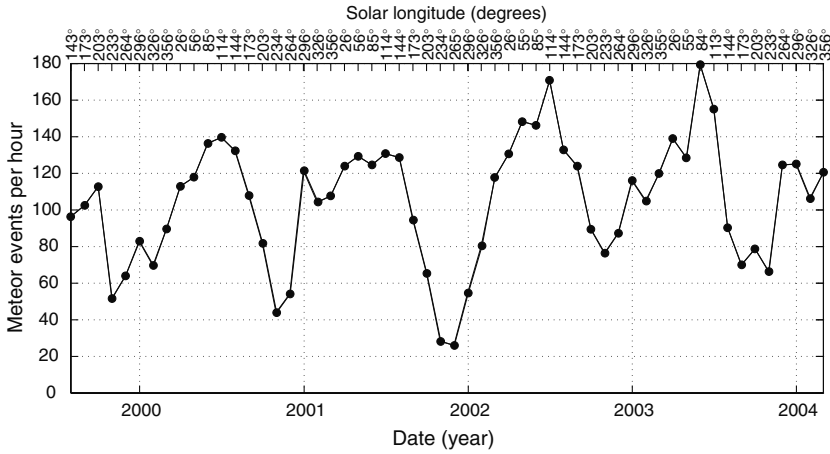


Figure 3. Monthly mean of the meteor rates with the north ecliptic pole (NEP) close to zenith at Esrange for the years late 1999 to early 2004.

2004. If the meteor flux were homogeneous, the meteor rate would be constant. However the flux is lower in winter than in summer, in agreement with Lovell (1954). The most prominent sporadic source is the north toroidal one during the first half of the year, and the north apex during the second half.

5. Conclusions

The largest difference in amplitude of the diurnal flux variation (from morning to evening) is at equatorial latitudes and is almost the same throughout the year. The lowest diurnal flux variation can be found at polar latitudes, where our observations show the highest degree of seasonal variation of the diurnal flux.

Radars at different latitudes see different sources. The sources also vary at different seasons.

Future work should include calculations on the collecting area of each radar for each sporadic source. Such a study would be useful in studying the strengths of the sporadic sources.

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MODELING THE SPORADIC METEOROID BACKGROUND CLOUD

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Abstract. The orbital distributions of dust particles in interplanetary space are revised in the ESA meteoroid model to incorporate more observational data and to comply with the constraints due to the long-term particle dynamics under the planetary gravity and Poynting–Robertson effect. Infrared observations of the zodiacal cloud by the COBE Earth-bound observatory, flux measurements by the dust detectors on board Galileo and Ulysses spacecraft, and the crater size distributions on lunar rock samples retrieved by the Apollo missions are fused into a single model. Within the model, the orbital distributions are expanded into a sum of contributions due to a number of known sources, including the asteroid belt with the emphasis on the prominent families Themis, Koronis, Eos and Veritas, as well as comets on Jupiter-encountering orbits. An attempt to incorporate the meteor orbit database acquired by the Advanced Meteor Orbit Radar at Christchurch is also discussed.

Keywords: Dynamics, interplanetary dust, interstellar dust, meteoroids, orbital distributions

1. Introduction

We have recently revised the ESA meteoroid model, the purpose of which is to predict fluxes on spacecraft in the Solar system. The revision was

* Work was done during D. Galligan's stay at the University of Canterbury.

motivated by several reasons. First, a mistake in computer code has been known to undermine the reduction of the Harvard Radio Meteor Project (HRMP) data (Taylor, 1995) that the previous meteoroid models (Divine, 1993; Staubach, 1996) were based on. Taylor and Elford (1998) pointed out that the orbital distributions in the HRMP survey were affected by yet another unaccounted bias hiding high-speed meteors. A new meteor survey was selected for incorporation in the ESA meteoroid model, i.e. the one conducted by the Advanced Meteor Orbit Radar (AMOR) at Christchurch, New Zealand, in the period from 1995 to 1999 (Galligan and Baggaley, 2004).

Second, several new meteoroid and dust data sets of high quality became available for incorporation in the model. The infrared emission from dust was surveyed by the Cosmic Background Observatory (COBE, see Kelsall et al., 1998). The dust detectors on board Galileo and Ulysses in deep space continued their successful operation and collected new impact events worthwhile incorporation in the model.

Third, the expansion of computer memory allows one today to detail the meteoroid distributions much better than before using large multi-dimensional arrays. In particular, the assumption of mathematical separability of the multi-dimensional distribution in position, velocity and mass of meteoroids postulated in (Divine, 1993) and replicated since then, can now be partially lifted. This new capacity of computers can be exploited to replace the empirical separable distributions of the previous models by the theoretical non-separable distributions of meteoroids obtained via dynamical simulations.

The new model constructed is outlined in this paper through a discussion of the sources and dynamics of interplanetary meteoroids, a brief introduction of semi-analytical models that are proven to be a good approximation to the complicated structures in the zodiacal cloud (Section 2), and subsequent tuning the model in accord with the observations (Section 3). A summary of our modeling efforts concludes this paper (Section 4).

2. Meteoroid Sources, Dynamics and Distributions

In the first meteoroid model update taking the orbital evolution of meteoroids into account, a simple view upon the sources of dust and the forces distributing it over the Solar system is adopted. The dust particles are assumed to be produced by asteroids, with the distinction between the main belt and some prominent families, and by those comets on Jupiter-crossing orbits. The governing forces are planetary gravity, with the emphasis on close encounters with Jupiter, and Poynting–Robertson effect, although analytical approximations are used to describe the distributing action of these forces.

The cumulative mass distribution of meteoroids $H(>M)$ is separated from the orbital distributions, i.e. the density $f(a,e,i)$ of particle orbits per unit intervals of semi-major axis a , eccentricity e and inclination i off the ecliptic plane. The model's mass distribution of meteoroids is based on the following considerations. In the collisional destruction experiments, the cumulative mass distribution of fragments was found to obey the power law $H^+(>M) = M^{-\gamma}$ with indices γ belonging to the range from 0.6 to 0.9. The time the meteoroids spend in a given orbital space bin T^- is determined by the removal process. The equilibrium number of particles in orbital space bin is then $H(M) = H^+(M) \times T^-$.

According to Grün et al. (1985), the particles bigger than $\sim 10^{-5}$ g have cross-section area sufficiently large to make the collisional destruction by the smaller particles the dominant removal mechanism. Due to the Poynting–Robertson effect, the particles smaller than $\sim 10^{-5}$ g are typically evacuated from the orbital space bin where they were produced before they can collide. In the ESA meteoroid model, the mass distribution $H(M)$ is postulated rather than derived, based on the cumulative mass distribution of meteoroid flux at 1 AU (Grün et al., 1985) reproduced in Figure 1, making the distinction between the dynamical regimes, the Poynting–Robertson drift and collisional destruction at the origin.

Dust from asteroids. In the asteroid belt, the dust production rate is defined to be proportional to the quantity of asteroids with numbers from (1) to (13902), neglecting the circumstances of the production efficiency of individual parent bodies, e.g. the effect of orbit-dependent collision frequency

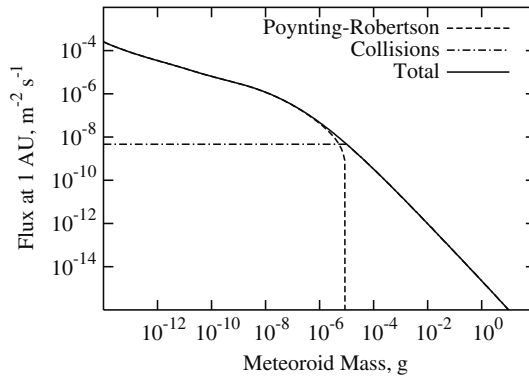


Figure 1. The mass distribution of meteoroids adopted in the new ESA model. It is based on the model by Grün et al. (1985) drawn with the solid curve, however, the full mass range is broken up into two subranges of different dynamics. Below the mass of 10^{-5} g, all particles are assumed to be perturbed by the Poynting–Robertson drag (dashed curve), and above this mass, all particles are to be perturbed by planetary gravity (dash-dotted curve). These sub-distributions are then combined with the orbital distributions obtained for the corresponding dynamical regime.

and difference of mass distributions of asteroids at different locations in orbital space. The large quantity of the asteroids as well as their confinement to low inclinations and eccentricities, allow one to generate the distributions of good statistical quality by simply counting the object numbers per orbital space bins.

The result of this operation is shown in Figure 2. The three-dimensional distributions $f(a,e,i)$ are integrated over two arguments in order to produce comprehensive plots. Dermott et al. (1984) discovered the asteroid dust bands extending from several asteroid families toward the Sun. In order to allow the families to play a role in the ESA meteoroid model, three distinct populations are recognized in the asteroid belt, the Themis and Koronis families ($2.8 < a < 3.25$ AU, $0 < e < 0.2$, $0 < i < 3.5^\circ$), Eos and Veritas families ($2.95 < a < 3.05$ AU, $0.05 < e < 0.15$, $8.5^\circ < i < 11.5^\circ$), and the main belt ($a < 2.8$ AU). The Themis and Koronis families are rather close in orbital space and are not separated in the meteoroid model. Similarly, the Eos and Veritas families, both being associated with the ten-degree band (Grogan et al., 1997; Dermott et al., 2002), are indistinguishably close for the model and merged into a single source.

The small particles from asteroid collisions and, even more importantly, from the disintegration of the big meteoroids in the collisional regime, are assumed to be distributed by the Poynting–Robertson effect. Gor’kavyi et al. (1997) provide the solution for the orbital density of dust evolving under the

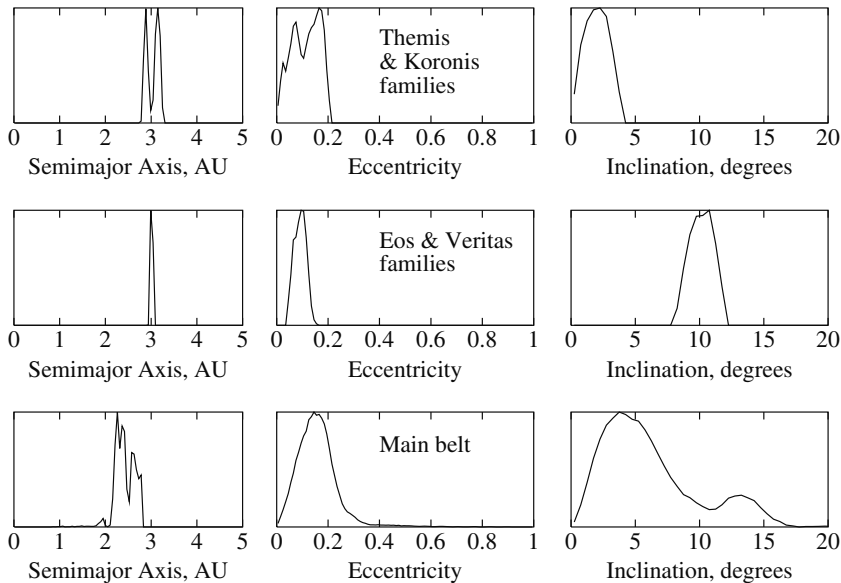


Figure 2. The orbital distributions of asteroids and big meteoroids ($M > 10^{-5}$ g). Shown are the relative frequencies.

pure Poynting–Robertson effect (found earlier by Leinert et al., 1983) as well as the one-dimensional distribution for a point source along any trajectory defined by the integral of motion due to Wyatt and Whipple (1950). The distributions of the small dust grains from asteroids obtained that way are plotted in Figure 3.

Dust from comets. The orbital distributions of meteoroids from the comets on Jupiter-crossing orbits cannot be defined as easy as the distributions of dust from asteroids. Because of a number of loss mechanisms, such as ejection from the Solar system by planets and fading out, very few comets are displayed at a time and listed in the catalogues. Moreover, the catalogues are prone to observational biases since the comet nuclei are revealed by gas and dust shed at high intensity at the low perihelion distances. The imperfect removal of these biases and low-number statistics would have degraded the quality of dust source distribution based on the catalogues.

The numerical integration of the equations of the motion of meteoroids has been done for a limited number of parent comets. By simulating the orbital dynamics of particles from comet Encke, Liou et al. (1995) demonstrated that the comets are necessary to account for the full thickness of the zodiacal cloud, with the dust from asteroids being confined close to the ecliptic plane. Liou et al. (1999) computed the trajectories of meteoroids of several sizes from comet Halley and its imaginary prograde clone. Cremonese et al. (1997) studied numerically the contributions of dust from comets

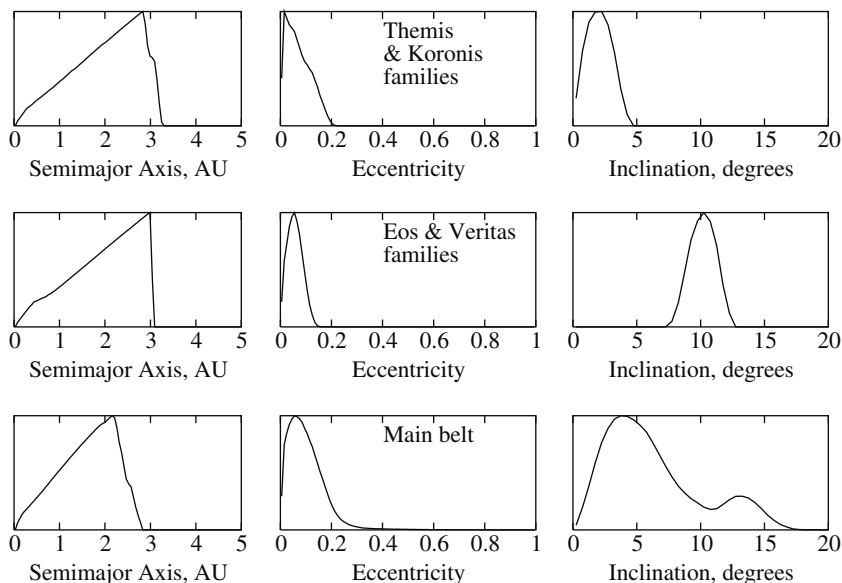


Figure 3. The orbital distributions of small meteoroids ($M < 10^{-5}$ g) from asteroids spiraling toward the Sun under the Poynting–Robertson effect. Shown are the relative frequencies.

Schwassmann-Wachmann 1 and Griegg-Skjellerup to the inner zodiacal cloud. Landgraf et al. (2002) additionally simulated the orbital evolution of meteoroids from the Edgeworth-Kuiper belt. These objects have been proven to be important sources of meteoroids yet altogether they are far from the full range of observable dust producers. Hughes and McBride (1990) presented results of a very ambitious simulation of trajectories of meteoroids (mass $> 10^{-3}$ g) from 135 short-period comets, placing 5000 particles in orbit of every parent comet. However, they did not consider the long-period comets. The meteoroid mass range scarcely covered by all numerical simulations is another problem.

Ironically, the orbital distributions obtained by means of numerical integration of test particle trajectories have the drawback of comet catalogues, i.e. the low number of objects to distribute. An attempt to build the four-dimensional distribution in orbit elements and mass would result in either low resolution or high noise. We have developed a method, however, to derive the orbital distributions approximately from several standard assumptions of statistical mechanics (Dikarev and Grün, 2004). The orbital distributions, g , of encountering particles form a family of functions parameterized by a single argument U , the encounter speed with Jupiter measured in the units of Jovian heliocentric velocity

$$g = n(U)I_E \frac{\sqrt{ae} \sin i}{2}, \quad (1)$$

where the function I_E was approximated by one whenever the heliocentric orbit of particle crosses a certain torus along the planet's orbit, and zero elsewhere. The torus' radius was found to be equal ≈ 0.5 AU for Jupiter by comparing the function (1) with statistical distributions obtained numerically. An exhaustive comparison with numerical experiments was performed by Dikarev and Grün (2004) to prove that the formula (1) is relevant unless resonances are taken into account: the distributions are plotted in their Figures 1–2. The resonances have to be described by a separate model.

The radiation pressure and the Poynting–Robertson effect are weak perturbations with respect to the effect of close encounters with Jupiter down to the $1 \mu\text{m}$ -sized meteoroids. Therefore, the orbital distributions g can be used to describe the populations of dust grains of all masses above $\sim 10^{-12}$ g.

There is a thin layer at the inner boundary of the encounter region in orbital element space, however, which the particles are likely to cross due to the Poynting–Robertson drag before they are scattered back into the encounter region. Having left the encounter region, the particles move under the Poynting–Robertson drag, i.e. they spiral toward the Sun in accord with (Wyatt and Whipple, 1950; Gor'kavyi et al., 1997).

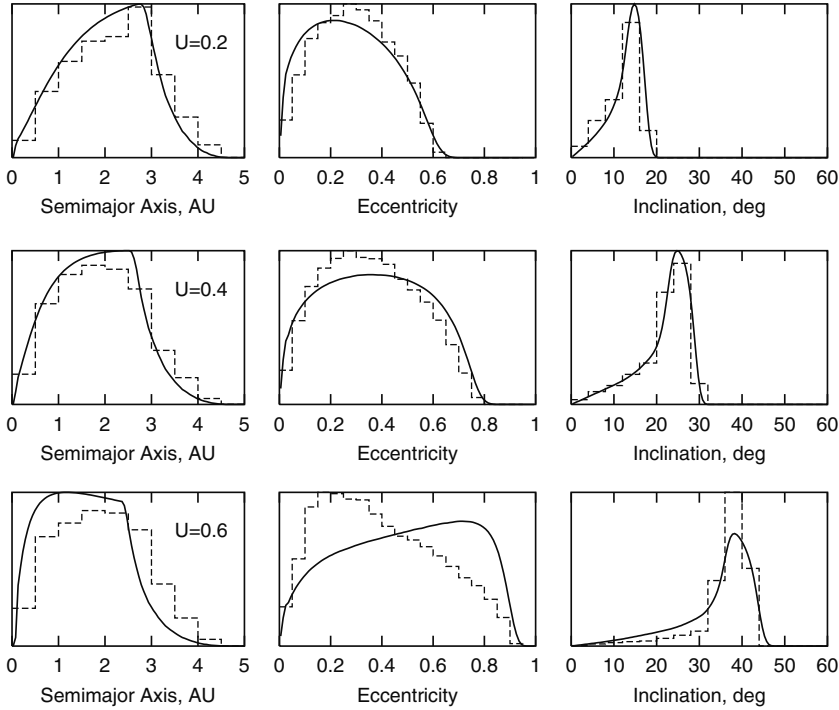


Figure 4. The orbital distributions of the particles of a radius $10\ \mu\text{m}$ leaking from the region of close encounters with Jupiter after being multiply scattered by this planet's gravity. The gravity of major planets excepting Mercury and Pluto is taken into account. The solid curves show the analytics, the dashed-line step-functions are numerically obtained statistics, all frequencies are in relative units. Labels indicate the encounter speed with Jupiter U , in the units of Jovian heliocentric speed.

The orbital distributions of the leaking dust grains escaping the region of encounters with different values of U are shown in Figure 4 along with their numerically obtained counterparts for a limited number of U 's. The full set of plots will be published in a larger paper that is currently under preparation.

The orbital distributions are multiplied by the cumulative mass distributions corresponding to the dominant loss mechanism, collisional or Poynting–Robertson (see Figure 1). The big meteoroids from asteroids $f_{1,2,3}^{\text{ast:big}}(a, e, i)$ are combined with the collisional (dashed) curve for masses $M > 10^{-5}\text{ g}$. The small dust grains spiraling from asteroids toward the Sun $f_{1,2,3}^{\text{ast:small}}(a, e, i)$ are assembled with the Poynting–Robertson (dash-dotted) curve for masses $M < 10^{-5}\text{ g}$. Meteoroids of all masses from comets in Jupiter-crossing orbits, the distributions of which are sliced into 24 populations of 0.1-wide, adjacent encounter-speed ranges $g_{1,\dots,24}^{\text{com:all}}$, are joined with the collisional curve for $M > 10^{-5}\text{ g}$, and with the Poynting–Robertson mass distribution for $M < 10^{-5}\text{ g}$. The orbital distributions of small meteoroids leaking from the

region of encounters with Jupiter also sliced into 24 populations in accord with their encounter speed at the time of boundary crossing $f_{1,\dots,24}^{\text{com;small}}$, are linked with the Poynting–Robertson curve.

In total, six populations of dust from asteroids are introduced in the model, and 72 populations of dust from comets and other parent objects on Jupiter-crossing orbits.

The interstellar dust (ISD) in the Solar system is represented by a mono-directional stream of particles, employing the approach of (Staubach, 1996). However, the cumulative mass distribution was changed to the more recently inferred curve of (Landgraf et al., 2000). The absolute normalization of the ISD flux was left free in order to allow for a new balance between the interplanetary and interstellar dust in the Galileo and Ulysses data, after a re-formulation of the interplanetary meteoroid populations.

3. Data Sets

Unlike the Divine and Staubach models, the new ESA meteoroid model is in no part based on the zodiacal light data any more. Instead, the infrared observations by the COBE near-Earth observatory are adopted as the new model reference. The COBE maps of infrared sky provide a wide spectral and surface coverage, while Divine (1993) used a few (< 10) of the zodiacal light intensities picked up from the Earth-based and Helios data sets, all measured at the same wavelength. Second, the visible emission from interplanetary meteoroids is significantly more difficult to simulate than the thermal emission, that means more assumptions and more uncertainties in modeling the zodiacal light data.

The most recent impact counts by the Galileo and Ulysses dust detectors are incorporated in the new model. The Ulysses data are up to the end of 2003, including the second near-perihelion ecliptic plane crossing. The data are simulated in more detail than by Divine, taking the direction information into account, yet with less assumptions than in the Staubach model about the mass and speed of the impactors inferred through rather uncertain relations from the raw detector measurements of impact-generated plasma.

The interplanetary meteoroid flux (IMF) at 1 AU by Grün et al. (1985) is incorporated in the new model, too. The treatment of the IMF is different from that of the previous meteoroid models, however. First, the flux is converted back into the crater size frequencies, using the equation given in Grün et al., (1985). And then the meteoroid model is fitted to the crater size frequencies instead of the IMF. It is necessary that crater size is determined by the mass and speed of the impactor. Grün et al. (1985), however, assumed a constant speed for all meteoroids of 20 km s^{-1} . In the meteoroid model, speeds are different, ranging from 0 to 71 km s^{-1} , and the model cannot be simply adjusted to the IMF without taking the speeds into account.

The cumulative mass distribution of meteoroids in the flux on spinning plate at 1 AU derived originally from the micro-crater counts on the lunar rock samples delivered to Earth by the Apollo missions, is converted back into the raw crater size distributions. Then the model is fitted to the raw distributions, taking both the mass and speed of meteoroids into account when predicting the crater sizes.

4. AMOR Radar Meteor Survey

The AMOR radar (Baggaley, 2001) measures echoes from meteors ablating in the Earth atmosphere and from these measurements the elements of pre-encounter heliocentric orbit are inferred. All registered meteors are archived in a database. The database can be used to produce the distributions of observed meteors in orbital elements. The correspondence between the observed distributions and the true space distributions at a mean mass threshold of $\sim 3 \times 10^{-7}$ g is established through a bias correction procedure (Galligan and Baggaley, 2004). The corrected distributions were produced in the form of three-dimensional array of numbers of meteoroids in rectangular cells covering semi-major axes from 0 to 6 AU, eccentricities from 0 to 1, and inclinations from 0 to 180° .

Attempting to incorporate the corrected distributions into the model showed that the AMOR distributions were not compatible with the COBE data and that it is not possible to fit the two data sets simultaneously under the model assumptions.

Figure 5 compares the latitudinal number density profiles of the zodiacal cloud at 1 AU obtained from different data sets by different teams. The distance of 1 AU from the Sun was chosen as the only one where the direct conversion of the AMOR orbital distributions into the number density is possible without extrapolations. Note, however, that in the alternative models (Leinert et al., 1981; Clark et al., 1993; Kelsall et al., 1998) the number density is mathematically separable in radial distance and latitude.

The plot shows that the AMOR distributions determine too wide a number density profile, incompatible with the other data sets, including COBE. One might argue that the radar is sensitive to the meteoroids of sizes different from the major contributors to the infrared emission and zodiacal light. In the ESA meteoroid model, however, both the radar meteors and the infrared emission are dominated by the particles of masses $< 10^{-5}$ g, which is a consequence of using the mass distribution of (Grün et al., 1985). This mass distribution ensures that 80% of total particle cross-section area (which the zodiacal light and infrared emission should be proportional to) belongs to the meteoroids from 10 to 100 μm in radius (10^{-8} to 10^{-5} g), the range embracing

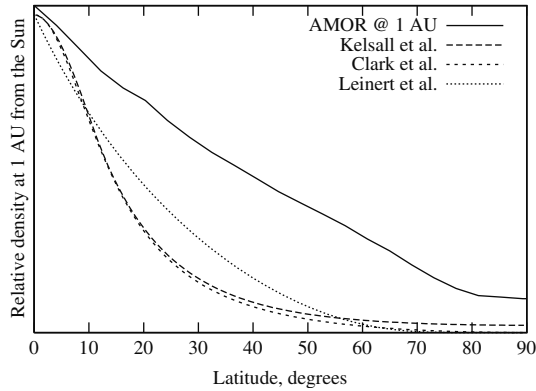


Figure 5. The latitudinal number density profiles inferred from the infrared observations by IRAS (Infrared Astronomical Satellite, see Clark et al., 1993), COBE (Kelsall et al., 1998), zodiacal light measurements (Leinert et al., 1981), and built based on the AMOR corrected orbital distributions (Galligan and Baggaley, 2004) at the distance 1 AU from the Sun.

the meteoroid sizes to which the AMOR is sensitive, and adequately described in the ESA model in the Poynting-Robertson regime.

Until the discrepancy between the AMOR orbital distributions and COBE latitudinal profile is resolved, either by incorporating unrecognized bias effects or further development of the model populations, the AMOR distributions cannot be incorporated in the present ESA model.

The orbital distributions of meteoroids based on the AMOR survey of radio meteors was the key data set to replace the old HRMP data, thus we continue to look for possibilities to converge the AMOR and COBE data.

5. The Best-Fit Model

The COBE infrared sky maps, Galileo and Ulysses impact counts, and the interplanetary meteoroid flux model were fed into the inverse problem solution program.

The quality of the fit obtained can be assessed in Figures 6–8. The comparison with COBE observations is shown in Figure 6. The infrared sky maps are plotted against solar elongation and “position” angle with respect to the Sun. The latter is measured from the ecliptic north *clockwise* about the Earth–Sun axis. At the solar elongation of 90° , the position angle of 90° is close to the apex of Earth motion, the position angle of 180° is close to the vertex.

The agreement is rather good. In fact, the standard deviation of the model residual in all filters is at the level of 4%.

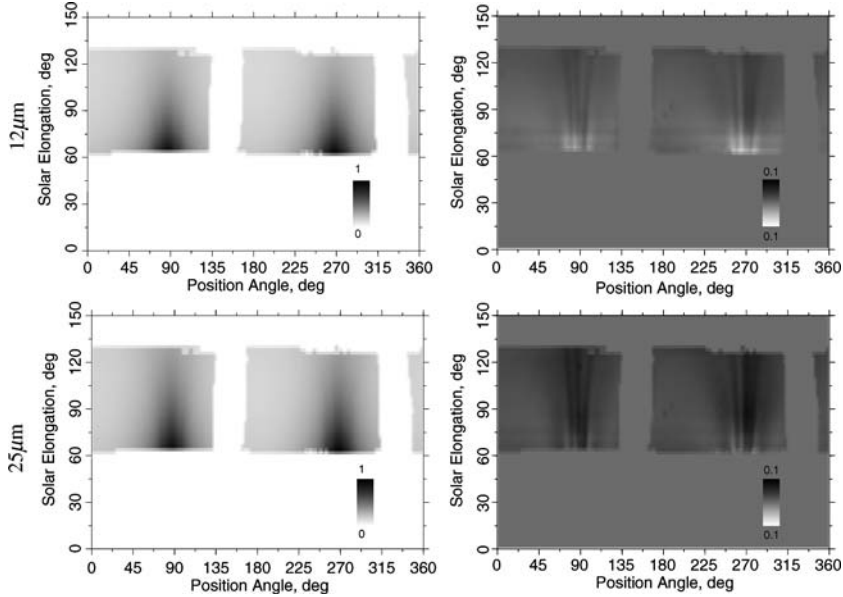


Figure 6. The best-fit model of two out of five COBE infrared sky maps (left) and its residuals, $O-C$ (right), in relative units, negative image. White areas on the left panels are the forbidden zones of high and low solar elongation and the galactic plane excluded from the data set to avoid interference.

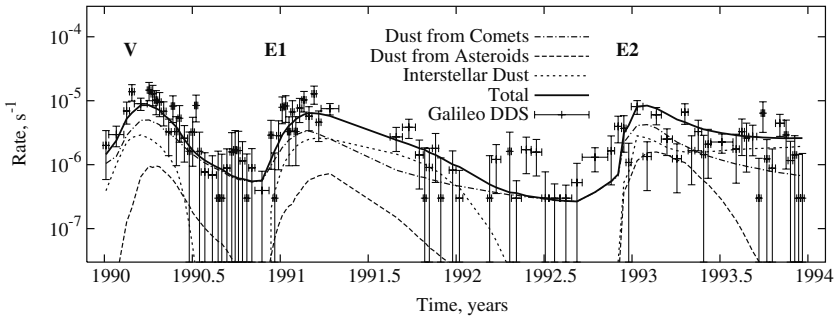


Figure 7. The best-fit model of the impact rates measured by the Galileo dust detector. Labels “V”, “E1” and “E2” mark the times of the Venus and two Earth close encounters.

The flux on Galileo and the model fit to it are shown in Figure 7. The uncertainties of flux inference from the impact count and the time bins within which the numbers were taken are indicated by the vertical and horizontal bars, respectively. Gaps correspond to the times of no measurement. The individual contributions due to the dust from comets, asteroids and from interstellar space are shown, as well as their total sum. The Ulysses data are also reproduced very well.

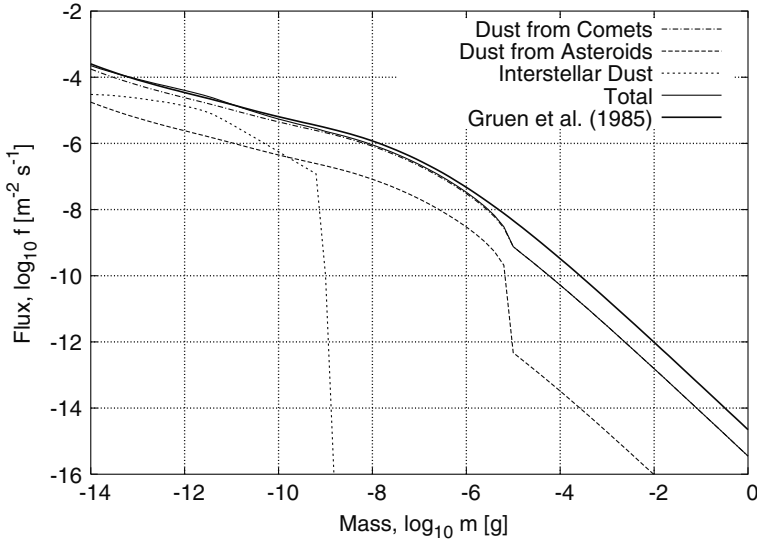


Figure 8. The best-fit model of the cumulative mass distribution of meteoroids in the flux at 1 AU, i.e. the Grün et al. (1985) model.

A distinct feature of the new meteoroid model seen in Figure 8 is the flux of asteroidal particles at 1 AU. It is one order of magnitude below the total flux at the meteoroid mass $< 10^{-5}$ g and even smaller at bigger masses. The asteroidal dust falls on Earth at a relatively small speed, so that it can not account for the flux observed without a sufficiently high number density. That high number density, on the other hand, is prohibited by the COBE observations. Therefore, the contribution of asteroidal dust to the flux at 1 AU has to be small, especially of the big meteoroids above 100 μm in size.

Note that there are relatively few asteroids on Earth-crossing orbits. Most of the asteroids never approach the Earth, and neither do big meteoroids ($> 10^{-5}$ g) of asteroidal origin. They are destroyed by collisions before the Poynting–Robertson effect drags them into the crossing region. Thus the cumulative flux of meteoroids from asteroids drops down abruptly at 10^{-5} g.

The total flux is also below the Grün et al. (1985) model in the big meteoroid range. This is the effect of the higher impact speeds of those meteoroids. The micro-crater size frequencies are reproduced very well in this impactor mass range.

6. Conclusion

A new meteoroid model for ESA to predict fluxes on spacecraft in the Solar system is developed. In this model, the orbital evolution of meteoroids is for

the first time taken into account in order to complement scarce data. The Poynting–Robertson effect, and the gravity of planets are taken into account to produce the orbital distributions of meteoroids from various known sources in the framework of approximate analytical solutions. These distributions are fitted to the infrared observations by the COBE taken in five wavelength bands from 5 to 100 μm over the range of solar elongation from 60° to 130° , the Galileo and Ulysses in-situ flux measurements, and the micro-crater size frequencies counted on the lunar rock samples retrieved by the Apollo missions. The AMOR orbital distributions could not be incorporated in the model since they fall in contradiction with the latitudinal number density profile of the zodiacal cloud behind the COBE infrared intensities. Improvements of the bias correction procedure or model formulation are required to fit to the AMOR and COBE data simultaneously.

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METEOROID ENGINEERING MODEL (MEM): A METEOROID MODEL FOR THE INNER SOLAR SYSTEM

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Abstract. In an attempt to overcome some of the deficiencies of existing meteoroid models, NASA's Space Environments and Effects (SEE) Program sponsored a 3 year research effort at the University of Western Ontario. The resulting understanding of the sporadic meteoroid environment – particularly the nature and distribution of the sporadic sources – were then incorporated into a new Meteoroid Engineering Model (MEM) by members of the Space Environments Team at NASA's Marshall Space Flight Center. This paper discusses some of the revolutionary aspects of MEM which include (a) identification of the sporadic radiants with real sources of meteoroids, such as comets, (b) a physics-based approach which yields accurate fluxes and directionality for interplanetary spacecraft anywhere from 0.2 to 2.0 astronomical units (AU), and (c) velocity distributions obtained from theory and validated against observation. Use of the model, which gives penetrating fluxes and average impact speeds on the surfaces of a cube-like structure, is also described along with its current limitations and plans for future improvements.

Keywords: Engineering model, interplanetary, sporadic meteoroids

1. Background

The sporadic environment consists of a diffuse background of meteoroids of cometary or asteroidal origin. They represent a continuous risk to spacecraft throughout the year, unlike meteor showers or storms, which occur when Earth passes very near the nodal crossings of comets, or, in some instances, asteroids. Although the risk to spacecraft is high during showers and storms, the sporadic meteoroid environment still poses a greater risk, as the integrated number is much greater than that of shower meteoroids, which are

only present for a relatively short period of time. Mitigating the meteoroid risks from such events can be accomplished by operational procedures, such as reorienting a vehicle to point sensitive equipment away from the radiant, or slewing solar panels edge on to minimize cross sectional area and closing shutters to protect sensitive optics. However, the constant threat presented by the sporadic meteoroid background must be reduced in the design of the vehicle, which can lead to significant engineering challenges. Often operators and designers choose to shield their spacecraft against the hypervelocity impacts. But, in the never-ending search for ways to reduce vehicle mass, questions inevitably arise... How much shielding is necessary and what parts of the spacecraft are most exposed?

To answer those questions, spacecraft designers need to have access to an engineering tool that accurately models the locations of the sporadic meteoroid radiants, with their relative strengths and proper velocity distributions. But there are several different methods for modeling these desired parameters. Some models rely on empirical fits to *in-situ* dust measurements from space probes, zodiacal light observations, lunar micro-crater counts, and ground based radar observations. Such fits, however, are limited by the quality of the data used in the fit, and must be used cautiously when designing vehicles destined for locations or particle sizes not covered by the observations. Another approach involves modeling the meteoroid orbital evolution from the distributions of the sporadic sources, relying only on observations to calibrate the model. This paper briefly addresses some of the shortcomings of empirical models of the past, and advocates the more physical alternative approach. We hope to address some of the issues that are of concern to spacecraft designers and mission analysts, specifically the flux of meteoroids of a certain mass or range of masses, the distribution of impacting speeds, and the directions from which those meteoroids are coming.

2. Other NASA Models

The models of the past were mathematical models, simple or complex numerical expressions fit to observations from a variety of data sources patchworked together. These expressions, though physically limited, defined the interplanetary meteoroid environment in terms of mass flux, velocity distribution, and meteoroid density. Most models also assumed that the sporadic background was omni-directional, an assumption that is known to be invalid.

The most popular NASA models are based on the "Interplanetary Dust Model" of Grün (Grün et al., 1985), a simple, easy-to-use equation that accurately fits the measured dust fluxes near Earth's orbit, but does not contain directionality and requires a single average meteoroid speed, rather than a distribution of velocities. The flux component of this model is

described in NASA Technical Memorandum (TM) 4527 (Anderson, 1994) and NASA Space Station Program SSP 30425. However, these documents also specify the use of a velocity distribution developed by Cour-Palais, based on photographic meteor velocity determinations, rather than the single speed advocated by Grün. The velocity distribution given in the NASA TM has an average speed of 17 km/s near Earth; for Earth orbiting spacecraft that number is 19 km/s, which is low compared to new information from radar observations. This older velocity distribution did not work well with the Grün flux because Grün's equation was meant to be used with a flux weighted average meteoroid speed of 20 km/s. That value was justified based on two reasons, the first of which being that cratering and destructive collisions depend on v^2 ; the average effect corresponding to a higher speed (over the average impact speeds on the moon from 13 to 18 km/s). Secondly, mutual collisions among meteoroids occur at higher speeds than impacts on the moon and on Earth because their eccentricity and inclination is generally larger than that of Earth, (Grün et al., 1985).

Older NASA meteoroid models, NASA SP-8013 (Cour-Palais, 1969) and SP-8038 (Kessler, 1970), define the sporadic meteoroid environment for mass ranges of 10^{-12} to 1 g. The mass density of meteoroids used in these models are 0.5 g/cm^3 with an average speed of 20 km/s, which was derived from photographic measurements (Dohnanyi, 1966), along with the assumption of the independence of mass and velocity. Again, these models are simple numerical equations that describe the flux of particles as a function of mass. The models also only deal with meteoroids of cometary origin, with the asteroidal contribution treated as negligible, a very highly disputed assumption. The flux equations were derived from measurements from meteoroid detectors of masses smaller than 10^{-6} g, and from Earth-based radar and photographic techniques for masses larger than 10^{-6} g.

Divine's (1993) "Five Populations of Interplanetary Meteoroids" model uses more complicated mathematics to obtain empirical fits for the orbital distributions of particles from a variety of data sources. In his paper, he describes his model as a numerical model, one which both supports the evaluation of concentration and flux. The original Divine meteoroid model was based heavily on the measurements and analysis of the dust populations, particles much less massive than the 10^{-6} g that most spacecraft designers consider to be the lower end of the threat regime. For the more massive particles, Divine relied on zodiacal light studies (Levasseur-Regourd and Dumont, 1980) and radar measurements to construct his model. Unfortunately, some biases and limitations associated with these data were not addressed. To be more specific, zodiacal light is mostly created by particles in the 10^{-8} – 10^{-5} g range (Grün et al., 1985), with the dominant contribution to the light coming from the lower end of this mass range, which barely extends into the threat regime. For larger particles, Divine relied on radar

measurements from Sekanina and Southworth's (1975) Harvard Radio Meteor Project (HRMP). Divine's speed distributions were based on this HRMP data, which provided the meteor orbital information. It was discovered by Taylor (1995) that a mistake had been made in the de-biasing of those speed distributions, which are now known to contain biases towards the lower speeds. The biases are due to an absent correction for the initial trail radius effect, which causes higher velocity meteors to be missed because of increased attenuation at increasing altitudes. Additionally, the Harvard dataset only applied to orbits that intersected the Earth's, leaving Divine to rely on interpolation methods for the un-sampled inner solar system. The valid distance for this radar data is 0.98–1.02 AU. Figure 1 shows the ranges in mass and distance from measurements collected for his model. It also shows the gaps in measurements and the limited amount of data on larger meteoroid particles of interest.

The current version of METEM, the model based on Divine's work, does not accurately model the sporadic directionality or velocity distributions. Figure 2 displays the discrepancy between METEM's directionality and what Earth-based radars believe it to be. The comparison is made for meteoroids with mass $m \geq 10^{-4}$ g encountering the Earth (Taylor and McBride, 1997). This discrepancy was discovered in private communications and analysis with M. Matney at Johnson Space Center (JSC). Additionally, METEM relies on a concentration dependence proportional to $r^{-1.3}$ (Leinert et al., 1983) which is

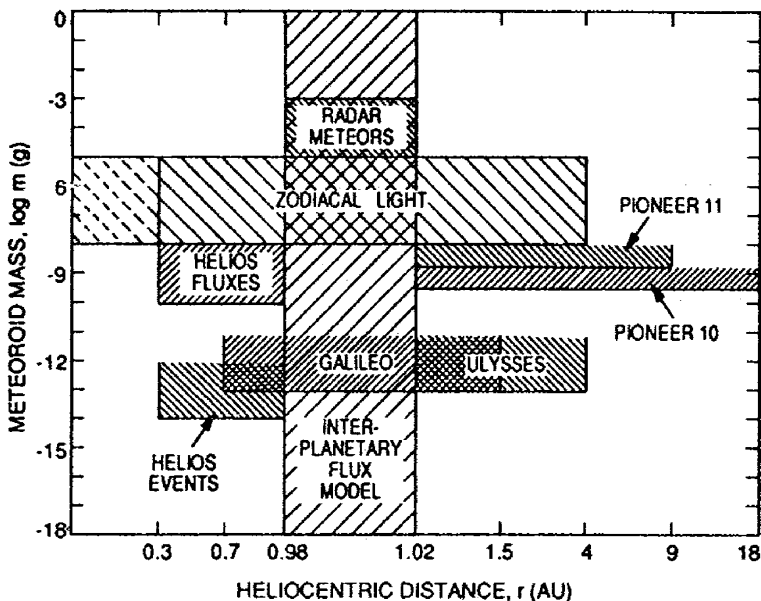


Figure 1. Coverage in mass and heliocentric distance for the data sets used in Divine (Divine, 1993).

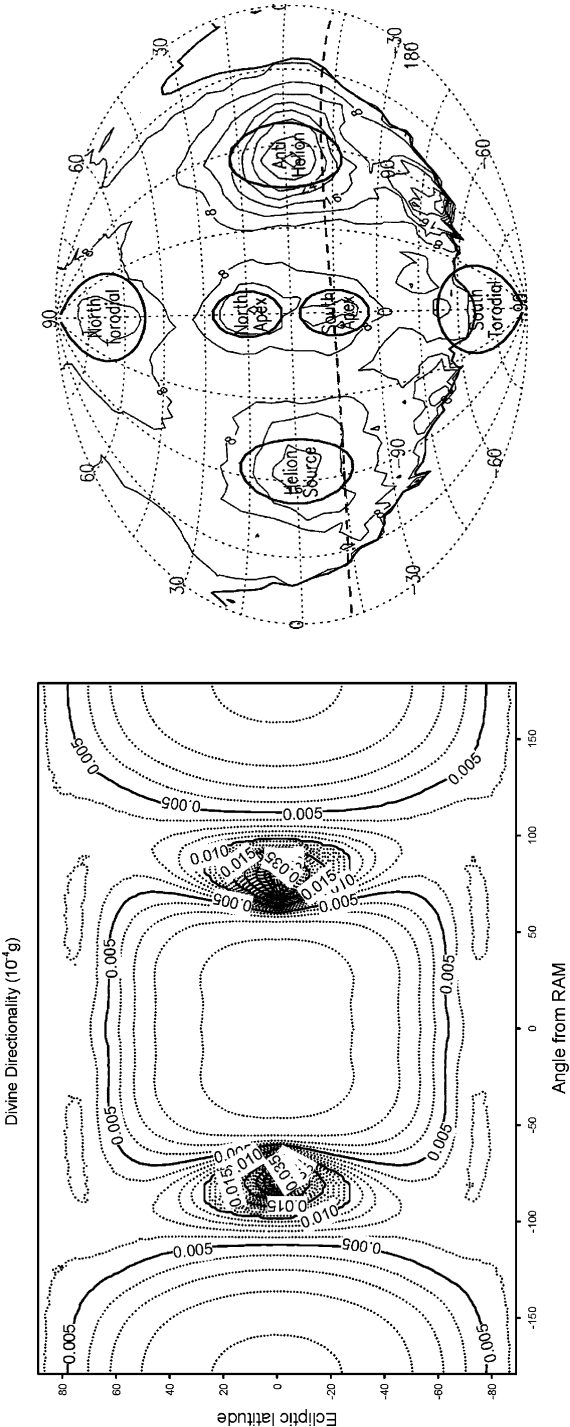


Figure 2. Comparison of METEM/Divine meteoroid directionality vs. Earth-based radar (Matney, 2004) (Taylor and McBride, 1997).

derived from zodiacal light concentrations and Helios data. Divine's model also adopts solar gravitational force as the only operative force acting on the particles in heliocentric orbits. The other forces such as planetary perturbations, non-gravitational forces (specifically radiation pressure), collisions etc. have been omitted from this model. The one population from METEM/Divine that most closely models the larger particles and best fits all the different measurement sources was the "core" population, the backbone of the model (Divine, 1993). The other populations were add-ons to cover special purposes. The average meteoroid density assumed for this core population is 2.5 g/cm^3 , with an average speed of 13.8 km/s at Earth.

Recently, Divine's model has been updated by members of NASA's Jet Propulsion Laboratory (Garrett et al., 1999) and Jehn (2000) to correct for the velocity bias and incorporate new meteoroid data and an updated user interface. The previous versions of METEM were very difficult for the general user requiring knowledge of the code to edit and run it (Garrett et al., 1999). The most recent version of METEM is still quite complicated and seems geared more to those interested in designing new spacecraft dust detectors rather than protecting specific surfaces from penetration.

Despite the more complex formalism of the Divine model, the fact remains that it and all of the previous NASA models are fundamentally empirical fits to observations, mathematical constructs with interpolation schemes for the areas beyond the measurements. The limitations of this approach have been previously discussed, and so another technique must be employed to model the environment, especially for the larger particles damaging to spacecraft. This approach must also be capable of allowing confident extrapolation into areas where observations are lacking.

We feel that this can be accomplished by adopting a "physics-based" approach, defined here to mean that the sources of sporadic meteoroids are tied to actual comet families and asteroids and that the steady-state distribution of the orbits of meteoroids released from these sources can be modeled under various forces to produce radiant and velocity distributions as seen by ground based radar (Jones et al., 2001). Once validated by an observation point (e.g., the Earth), the model can be extended beyond this point to be used any place where the sources and the physics incorporated within the model are valid. Unlike the previously described numerical models, MEM follows this physics-based approach, opened by Leinert, (Leinert et al., 1983).

3. Meteoroid Engineering Model (MEM)

Deficiencies in the current meteoroid models spurred a recent effort by the SEE program to develop a new meteoroid engineering model that

incorporated a physics-based approach to modeling the sporadic environment, with validation against radar observations (Jones, 2003). The task was to construct a model that could predict the concentration and velocity distribution of meteoroids within the inner solar system from 0.2 to 2.0 AU, using observational measurements to constrain the physical model, rather than build one based on empirical fits. Because micrometeoroid detectors on board space probes and satellites have observed highly directional fluxes of interplanetary dust particles that vary in particle size (Grün et al., 1985) and NASA is planning large oriented spacecraft such as Solar Sails and James Webb Space Telescope, incorporating directionality was of great importance in this model.

Previous work done by Jones and Brown (1993) show that the sporadic meteoroid environment as observed from Earth can be described by four major sources in six radiant distributed symmetrically about the celestial sphere in sun-centered ecliptic coordinates. The primary sources of the Helion/Anti-Helion, North and South Apex, and North and South Toroidal radiant are Jupiter family comets, or JFC's, long period comets, and Halley family comets, respectively. The asteroid component, not very well understood, at least in terms of its strength relative to the cometary sources, is also modeled. Some specific details on the physics behind the model are described in following paragraphs.

First, MEM assumes that comets are a major source of sporadic meteoroids. The orbits of the comets are distributed symmetrically about the ecliptic pole (ascending nodes and arguments of perihelion are uniformly distributed), so that the important parameters are a , the semi-major axis, e , the eccentricity, and i , the inclination. Asteroids also contribute to the meteoroid population, and the model incorporates distributions in a , e , and i provided by J.C. Liou at NASA's Johnson Space Center. Here again, the assumption of axial symmetry about the ecliptic pole is made.

It was realized early on that incorporating the effects of planetary perturbations on the meteoroids increases the computational burden tremendously; therefore those effects were ignored. One justification for the neglect of this effect is that, over the long-term, the average gravitational perturbing force on those meteoroids that don't make a close encounter with a planet is azimuthally symmetric. In these cases, the meteoroid orbit is changed slightly since the planet's mass is small relative to the sun and the main perturbation is a precession of perihelion, which does not significantly change an azimuthally symmetric orbital distribution. The model does include the important dust producing mechanism of catastrophic collisions and the Poynting-Robertson (PR) effect in a parametric model that has been fitted to observations made with Canadian Meteor Orbit Radar (CMOR) system. Other effects not considered in this model are very close planetary encounters

and mean motion resonances, which probably affect only a relatively small fraction of the meteoroid population.

Given all the forces and assumptions, one is then able to estimate the steady-state orbital distributions of the ejected meteoroids and convert these distributions into a flux of particles that would be observed from Earth or a spacecraft. The first step is to determine the concentration of meteoroids $S(r)$ as a function of heliocentric distance r , from the Sun. Where Q is the aphelia, and q is the perihelia distances. This can be done by invoking the standard expression given by Opik (1951), Kessler (1981) and Steel and Elford (1986):

$$S(r) \propto \frac{1}{r} \int \int \frac{N(Q, q)}{(Q + q) \sqrt{(r - q)(Q - r)}} \quad (3.1)$$

In developing distributions for the sporadic complex, comets can be organized initially by period and Tisserand parameter. The two main groups considered are the short-period and the long-period comets. The short period group has orbits which are closely aligned with the ecliptic and their periods are less than 200 years; the long-period comet orbits are essentially isotropically distributed with periods greater than 200 years. In addition, the short-period group can be further categorized into two main families: the Jupiter family of comets with periods less than 20 years and Tisserand parameters greater than 2.0 and the Halley family with periods greater than 20 years and Tisserand parameters less than 2.0.

With the main groups of comets now organized into the Jupiter family, Halley family and Long-period comets, meteoroid production rates can be assessed. It is important to note that the orbital distribution of the parent comets is not the same as the source production function since those comets that come close to the Sun will produce correspondingly more meteoroids than the comets with more distant perihelia. Several authors have shown that the threshold for the sublimation process to occur is around 2.3 AU (Delsemme, 1976; Jones, 1995). When the comet comes closer to the sun than 2.3 AU, sublimation predominates over radiation. To describe this relationship, the true anomaly θ_c at which the distance to the Sun is 2.3 AU is described by equating the sublimation rate per unit area to the solar flux, and applying appropriate averaging. Also, if the assumption is made that the composition of comets is uniform (the ratio of dust to ice is constant), then it follows that the amount of meteoric material released is proportional to the amount of ice sublimated as the comet passes close to the Sun. The average rate of production of meteoric material can then be given by

$$P_{\text{avg}} \propto \frac{\theta_c (1 - e)^2}{q^2 \sqrt{1 - e^2}} \quad (3.2)$$

where e is the eccentricity, q the perihelion distance, and θ_c is the true anomaly. After applying this equation to the groups of comets named above, one finds that the Jupiter family accounts for 91% of the meteoric material, the Halley family 5% and the Long-period family 4%. Of the Jupiter family of comets, only a subset are meteoroid producing comets, those with Tisserand parameters close to 2.8. Applying these definitions and limitations described here to the Marsden Catalog of Cometary Orbits (Marsden, 1989), the following results are obtained.

Analyses of the zodiacal light observations by the Helios I and II space probes show strong evidence that the density of interplanetary dust varies with heliocentric distance according to $r^{-1.3}$ (Leinert et al., 1983). Recall that the particles responsible for the majority of the zodiacal light are smaller than typical penetrating meteoroids but not so small as to be removed by radiation pressure; therefore it is reasonable to assume the same dependence on heliocentric distance r for the larger particles (Grün et al., 1985). These same zodiacal light observations also imply that the orbital distributions of interplanetary particles have azimuthal symmetry. It is logical then to assume that the source distributions can be considered separable into a part, $N(Q, q)$ that depends only on the the aphelion distance Q , the perihelion distance q , and another part that depends only on the orbital inclination.

As our model follows the same observed $r^{-1.3}$ dependence of particle concentration on distance from Sun, a constraint is placed on the aphelion distribution of the helion/anti-helion source to be identical to that of their parent Jupiter family of comets. The perihelion distribution is unknown, due to observational biases and the unknown effects of the variation of sublimation efficiency with age. This being the case, the following has been chosen as the form for the distribution function of Jupiter family perihelia:

$$n(q) \propto \{1 - (q/2.3)^m\}^t (q/2.3)^{m-1} \quad (3.3)$$

The aphelia distribution can be described by a gaussian where $\bar{Q}$ is the mean aphelion distance and σ the associated standard deviation:

$$n(Q) \propto e^{-((Q-\bar{Q})/\sigma)^2} \quad (3.4)$$

In order to develop the distribution of inclinations for the Jupiter family group, it is necessary to assume that the orbital inclinations of those particles in the threat regime are not significantly changed when they are released from their parent comets. However, the distribution of inclinations for the entire set of particles associated with the Jupiter family comets is not necessarily what needs to be considered; rather, emphasis will be placed on those particles with orbital planes capable of intersecting that of the Earth. This

distribution is different from the whole set of Jupiter family particles and can be described by:

$$n(i) \propto e^{-(i/15.9)^2} \quad (3.5)$$

An interesting aspect of function (3.3) is that not only does it go to zero beyond 2.3 AU (as it should), but it is also extremely flexible because of the parameters m and t . The Q and q distributions can be generated separately as they appear to be uncorrelated. With a given $\{m, t\}$ the particle concentration, $S(r)$, becomes

$$S(r) \propto \frac{1}{r} \sum_t \frac{1}{(Q_t + q_t) \sqrt{(r - q_t)(Q_t - r)}} \quad (3.6)$$

Other factors must be invoked to determine the values that best fit all the observations. The zodiacal light observations show that the particle concentration increases with decreasing heliocentric distance, which seems to imply some mechanism, such as the PR effect, that transports particles towards the Sun. An important factor in this effect is the length of time the particles are likely to survive. Consideration of the two processes active in reducing the particle population reveals that catastrophic collisions with other meteoroids are more important than the erosion resulting from collisions with much smaller particles, (Grün et al., 1985). As the majority of the short-period particles have low inclinations, one can assume that for those particles there is no dependence of the collisional lifetimes on orbital inclination. The rate of collisions with particles of similar size varies as $q/r^{1.3} a^{1.5}$. The relative collision speed, v_{rel} is determined mainly by collision geometry and can be described by:

$$v_{rel} \propto \frac{1}{\sqrt{r}} \quad (3.7)$$

The relative number of such particles depends on their mass distribution which is modeled as a power law (Grün et al., 1985):

$$dn \propto m^{-2.34} dm \quad (3.8)$$

where n is the particle number and m the meteoroid mass. These factors can be combined to produce a rough expression for the collision lifetime, t_{coll} :

$$t_{coll} \propto q^{1.64} a^{1.5} \quad (3.9)$$

The effect of PR aging on the orbital parameters of the particles has been calculated by Wyatt and Whipple (1950), who published equations for the rate of change of semi-major axis, a , and rate of change of eccentricity, e , as functions of a variable $\alpha = 3.55 \times 10^{-8}/s\rho$ AU/year, where s and ρ are the

radius and density of the particle in c.g.s units. This simulation uses about 5×10^5 particles evolved over several thousand years; direct integration of the Wyatt and Whipple equations would take very long computation times. Consequently, their scheme has been modified by using numerical approximations for the time integrals, making the calculations of the evolved orbits very fast. It is now appropriate to introduce another quantity, $\tau_{\text{pr}} = 1/4\alpha$, which is the time for a particle initially in a circular orbit at 1 AU to spiral into the Sun. For a 10^{-4} g particle with density 1.0 gram/cm^3 , $\tau_{\text{pr}} = 2 \times 10^5$ years. To avoid limiting collisional lifetime to particles of a specific mass, it is convenient to express that relationship in terms of τ_{pr} ; in these generalized time units equation 3.9 may be rewritten as:

$$\tau_{\text{coll}} = f q^{1.64} a^{1.5} \quad (3.10)$$

where f is the ratio of the collisional lifetime to the PR lifetime of a particle in a circular orbit at 1 AU. This approach is not ideal, as the probability of catastrophic collision changes during the orbit evolution. However, to avoid a detailed and computationally complex scheme, perhaps the details can be hidden in a proper choice of the parameter f . Therefore, the orbital distributions can be described by three parameters: m , t , and f , which can be determined through comparisons with observations, in particular those of zodiacal light and CMOR radar data. The CMOR data was used because its 3-frequency observations of meteors provided the material needed for Campbell-Brown and Jones (2003) to develop a model of meteor ablation that agrees well with the data. The 3-frequency setup also allowed for the estimation of the velocity bias due to the initial trail radius effect. The following table (Table I) compares the measured characteristics of the helion/anti-helion sources according to Brown (1994) and Jones and Brown (1993) to an analysis of radar meteor data from the IAUMDC (Lindblad, 1995). The CMOR data has had three corrections applied to it – the initial trail radius effect, deceleration of the particle in Earth’s atmosphere (Baggaley et al., 1994), and the increase in speed due to Earth’s gravity.

An initial comparison of this model’s source concentrations and velocity distributions were made against the HRMP data by Jones et al. (2001). Even though the HRMP data had velocity biasing errors affecting the relative strengths of the sources, one can make a comparison to a given source to see

TABLE I
Rader determination of helion/anti-helion characteristics

	HRMP	CMOP (2003)
Helion long.	341–345 deg	338 deg
Antihelion long.	193–201 deg	202 deg
< V_g >	31.7 km/s	34.4 km/s

if the model's distributions accurately match the radar observations. Taylor (1995) has shown that the biases between fast and slow meteors doesn't change the velocity distribution of an individual source very much. The Harvard data was the only known published data set of radar meteors at the time this model was created and some basic comparisons can be made, provided the biases are understood. Jones et al. (2001) did show that the orbital distributions described in MEM do accurately match the radar speed distributions and source concentrations very well, which is a good indication that the model orbital distributions are reliable, at least to first order. Current versions of these distributions were successfully compared to the newer CMOR data because of the improved bias corrections and data quality.

The process of deriving the distributions for the particles ejected from the long period comets is complicated by the fact that little is known of the variation of their concentration with heliocentric distance. Previous studies have shown that the space density of the high speed meteors attributed to the long period source are a small fraction of that produced by short-period comets. It was realized that, because the orbits of the long-period comets are so extended, the distribution of the dust they produce is dominated in the inner Solar System by the distribution of their perihelia. Everhart (1967) studied the effects of observational bias on the orbital distribution of long-period comets and proposed a likely distribution, which has been modified to account for sublimation. The distribution for the inverse semi-major axis, $b = 1/a$, is described exponentially as:

$$n(b) \propto e^{-b/129} \quad (3.11)$$

Since the orbital poles are distributed isotropically for long-period comets, the distribution of inclinations are uniform between 0° and 180° .

Collisions are incorporated in a similar manner as for short-period comet particles, except that in the long-period case, the inclinations do matter. The majority of collisions will occur with the dust from the short-period comets because they reside close to the ecliptic. So the long-period particles with low inclination orbits will most likely collide with the short-period particles aligned with the ecliptic disc. Again, the collision lifetime are characterized by the parameter f , but an additional factor is now introduced to allow for the orbital inclination of particles in retrograde orbits. Those particles with retrograde orbits close to the ecliptic will have shorter lifetimes than those with prograde orbits because of the relative impact speeds. The collision lifetime for long-period particles is therefore:

$$\tau_{\text{coll}} = f q^{1.64} a^{1.5} e^{\frac{1}{2}(\frac{-180}{11.2})^2} \quad (3.12)$$

Consideration of the inclination distribution of the toroidal source makes it clear that the distribution is not isotropic, as that would only add to the

strength of the radiants in the direction of the apex. It is reasonable to conclude that the toroidal source of sporadics is not from long-period comets but are somehow related to the short-period comets or asteroids. Tentatively, they are assigned then to the Halley family of short-period comets with periods between 20 and 200 years. As the inclinations of the observed toroidal meteors are high, their orbits place them out of the ecliptic and therefore don't suffer much from collisions with ecliptic dust. The assumption was then made to ignore the effects of collisions for the toroidal source. Lacking information regarding the observational selection effects, the distribution of perihelia for this Halley family group is of the same form as the long-period perihelia distribution, Equation (3.3). The inverse semi-major axis distribution was taken to be uniformly distributed between about 0.029 and 0.136/AU, corresponding to the range of the Halley family group. The inclination distribution is assumed to be gaussian.

Orbital distributions for the asteroidal component were provided by J.C. Liou, based on infra-red observations of 25μ asteroidal particles. Since asteroidal meteors are difficult to detect, there are no observational constraints from radar meteor observations, hence no adjustable parameters. No inter-particle collisions are modeled for this population; however, it is expected not to influence the final results since those orbits have low eccentricities and the included PR effect only circularizes them. Also, as the orbits of the asteroidal meteoroids are more circular, only orbits with semi-major axes close to 1 AU will be observable from Earth, and they should be the same whatever their age.

In the model, a Monte-Carlo method was used in the generation of semi-major axes for the asteroidal component, and then the normalized distribution function was approximated by a 5th order polynomial:

$$n(a) = \sum_{k=0}^5 c_k a^k \quad (3.13)$$

The eccentricity distribution, ecc , is described well by a Weibull distribution:

$$n(ecc) \propto e^{-(ecc/0.158)^{2.24}} (ecc/1.58)^{1.24} \quad (3.14)$$

The inclination distribution is characterized by a double gaussian as

$$n(i) \propto 8.57e^{-(i/2.57)^2} + 2.57e^{-(i/8.57)^2} \quad (3.15)$$

Several of the parameters describing the orbital distributions for the sources are educated guesses and rough fits. However, more time and observations will result in improved distributions. Amazingly, even with these simple assumptions, the source radiants constructed from the model

distributions produce very agreeable results when compared to the radar meteor observations.

A brief summary of the engineering approach adopted by MEM can now be summarized. The fundamental core of the program, some precepts of which are outlined above, calculates integral meteoroid fluxes and impacting speeds relative to the spacecraft. In this core, meteoroid velocities and spatial densities are derived from distributions of cometary and asteroidal meteoroid orbits. From these relative velocities and spatial densities, a meteoroid flux is calculated at the spacecraft location, and then arranged in a directional grid form, each cell having the appropriate flux strengths and velocity weights. Inherent in the computations are the debiasing, mass-weighting, initial trail radius correction, and relative source strength corrections applied by Campbell-Brown and Jones (2003). These results are then used to construct the mass-limited or penetrating meteoroid flux onto the spacecraft by employing a ray tracing algorithm to integrate the flux from the sporadic radiants over various surfaces of the vehicle. The model is capable of computing the flux of mass ranges damaging to spacecraft, 10^{-6} –10 g. For hypervelocity impact shielding, two single-wall penetration equations, those of Fish-Summers and Cour-Palais, are implemented, under the assumption that the density of the meteoroids is 1.0 g/cm^3 . These equations were chosen because they give adequate predictions of aluminum plate impact tests, with that of Fish-Summers being the more conservative. More information about these penetration equations can be found in Elfer (1996). Final results are presented as flux of particles greater than and including a specific mass with average impacting speeds on each surface of a cubical spacecraft, along with the normalized velocity distribution for the entire spacecraft.

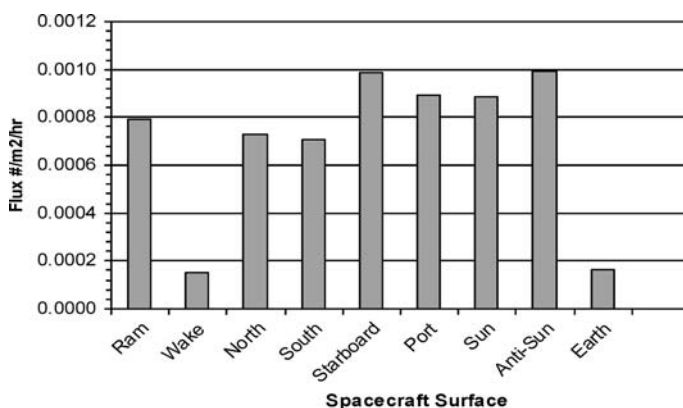


Figure 3. Flux on Spacecraft Surfaces 1 AU, 10^{-6} g mass.

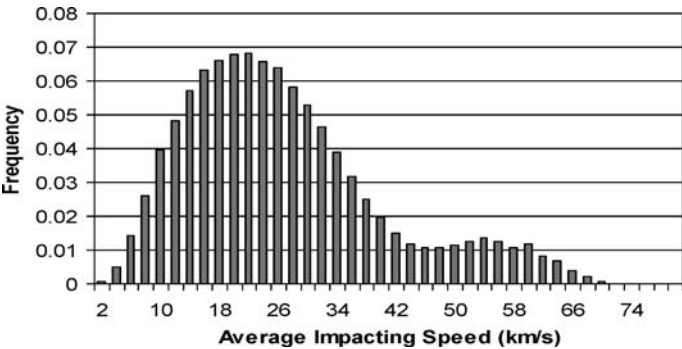


Figure 4. Total Speed Distribution.

4. Results from MEM

Below are some results from a test case from MEM Version 1.0. This scenario models a cubical spacecraft in a nearly circular heliocentric orbit of 1 AU. Penetrating fluxes are not calculated; the choice has been made to compute the flux of meteoroids greater than and including 10^{-6} g. Figure 3 is a graphical representation of flux on each surface of the vehicle. For zero eccentricities, the position vector and the velocity vector are perpendicular and therefore the starboard and port surfaces will be equivalent to the sun and anti-sun surfaces. If an elliptical heliocentric orbit is chosen, those surfaces will display different flux values. Figure 4 represents the distribution of particles at the spacecraft location and Table II describes the average impacting speed on each surface.

Note that MEM predicts an average flux weighted speed of meteoroids of 23.9 km/s at Earth, compared to the Grün value of 20 km/s. This new value agrees with the observations from the CMOR system.

5. Current Limitations and Future Plans

The current release of MEM, delivered to the SEE program in May 2004, does not contain gravitational focusing, so it is applicable only for spacecraft in

TABLE II
Average Impacting Speed (km/s) by Surface

Ram	Wake	North	South	Starboard	Port	Sun	Anti-Sun	Earth
26	21.6	24	24.1	24.2	24	24	24.2	21.4

interplanetary space within the inner Solar System. It is quite obvious that the relative strengths of the sources, especially that of the asteroidal component, and the biases in the observations (especially those from radar) used to calibrate the model are all areas that need further work. Consistency with other data, such as that from LDEF and photographic/electro-optical systems, must be investigated. However, the engineering focus of this model requires an accurate environment description only of particles of sufficient mass to damage spacecraft; we are quite aware that it may not adequately depict the “dust” environment, consisting of particles smaller than $10\ \mu$ in diameter. This is to be expected, as other forces, such as electromagnetic (Lorentzian), and other sources (interstellar) begin to come into play as we move down in the mass scale.

Future releases will incorporate gravitational focusing so that the program is applicable near planets, making it useful for lunar or Martian mission designs. Other updates will include additional surfaces pointed towards the sun/anti-sun and earth directions, spinning surfaces, different spacecraft orientations, velocity distributions on each surface, and additional penetration equations, perhaps even user defined ones. Updates to the physics model will be included as more data is analyzed, and we fully anticipate incorporating annual variation in the sporadic background, including distributions for meteor densities (already in work), and extending the model beyond Mars.

6. Summary

This recent research effort has produced a new tool that will help spacecraft designers mitigate the risks posed by sporadic meteoroids. The directionality effects, source strengths and velocities presented in this model are an improvement over past models and with future releases and updates in the penetration equations and spacecraft orientations, it is our hope that this will provide a more reliable meteoroid environment for the design of interplanetary spacecraft.

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MSFC STREAM MODEL PRELIMINARY RESULTS: MODELING RECENT LEONID AND PERSEID ENCOUNTERS

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Abstract. The cometary meteoroid ejection model of Jones and Brown [*Physics, Chemistry, and Dynamics of Interplanetary Dust, ASP Conference Series* **104** (1996b) 137] was used to simulate ejection from comets 55P/Tempel-Tuttle during the last 12 revolutions, and the last 9 apparitions of 109P/Swift-Tuttle. Using cometary ephemerides generated by the Jet Propulsion Laboratory's (JPL) HORIZONS Solar System Data and Ephemeris Computation Service, two independent ejection schemes were simulated. In the first case, ejection was simulated in 1 h time steps along the comet's orbit while it was within 2.5 AU of the Sun. In the second case, ejection was simulated to occur at the hour the comet reached perihelion. A 4th order variable step-size Runge–Kutta integrator was then used to integrate meteoroid position and velocity forward in time, accounting for the effects of radiation pressure, Poynting–Robertson drag, and the gravitational forces of the planets, which were computed using JPL's DE406 planetary ephemerides. An impact parameter (IP) was computed for each particle approaching the Earth to create a flux profile, and the results compared to observations of the 1998 and 1999 Leonid showers, and the 1993 and 2004 Perseids.

Keywords: Comet, comet ejection, Leonids, meteor, meteor shower, meteoroids, model predictions, numerical integration, Perseids

1. Introduction

The Marshall Space Flight Center (MSFC) meteoroid stream model simulates particle ejection and subsequent evolution from comets in order to provide meteor shower forecasts to spacecraft operators for hazard mitigation and mission planning purposes. This paper is concerned with simulating the evolution of the Leonid and Perseid streams associated with comets 55P/Tempel-Tuttle and 109P/Swift-Tuttle, respectively. The model is in a fairly early phase of development, thus the results reported here are preliminary. The immediate aim was to compare the peak solar longitudes resulting from the model with observations of past Leonid and Perseid encounters.

2. Model

2.1. OVERVIEW

In modeling particle ejection and subsequent evolution from comets Tempel-Tuttle and Swift-Tuttle, the workload is broken into three parts. First the test particles are created, then their positions and velocities are integrated forward in time, and finally the particles are extracted at specific times of interest.

At the first step, the JPL HORIZONS Solar System Data and Ephemeris Computation Service is used to create cometary ephemerides. Particle state vectors are generated for each line in the ephemeris while their physical properties are determined from a uniform, random draw on $\log \beta$, where β is the ratio of radiation pressure to the Sun's gravitation, and an assumed density. Two separate ejection schemes (two sets of state vectors) are simulated: Timestep and Perihelion. Ejection is simulated in 1 h time steps along the comet's orbit while it is within 2.5 AU of the Sun, hereafter referred to as the Timestep case. Ejection occurring only at the hour of perihelion passage is referred to as the Perihelion case. The model of Jones and Brown (1996b) is used to determine particle ejection velocity. The particle velocity far from the comet is given by

$$V_{\infty} = 41.7(\sin(\alpha/2))^{0.37}(\cos z)^{0.519}R_c^{1/2}m^{-1/6}\rho^{-1/3}r_h^{-1.038}$$

where α is the semi-angle of the spherical cap of ejection, z is the local solar zenith angle, R_c is the comet radius, m is the particle mass, ρ is the particle density, and r_h is heliocentric distance. Sublimation is taken to occur on the day side of the comet within a constrained cap angle (α); for further description of the cap angle and the other parameters, the reader is referred to Jones and Brown (1996b) and Jones (1995). Other studies (e.g. Brown and Jones, 1998; Göckel and Jehn, 2000; Welch, 2003) have investigated this ejection velocity model.

At the second step, a 4th order variable step-size Runge–Kutta integrator is used to integrate meteoroid position and velocity forward in time, accounting for the effects of radiation pressure, Poynting–Robertson drag, and the gravitational influences of 7 planets, Venus through Neptune. JPL's DE406 is used to compute the positions of the planets; interpolation is done via cubic spline. Integration of the particle ensemble is performed on 9 dedicated AMD Athlon™ 64-bit FX processors. The CPU time for each case, as discussed in Section 2.2, is approximately 5 days for the Leonids and 2 weeks for the Perseids.

In the last step, particles are extracted within 0.01 AU of Earth within 1 week before and after the expected shower peak. The node-Earth distance

for each particle is computed, along with an impact parameter (IP) for each meteoroid approaching Earth. The IP is defined as follows

$$\text{IP} = (R_E + h_{\text{atmos}})/D$$

where R_E is the radius of the earth, h_{atmos} is the height of the atmosphere, and D is the Earth-particle distance at nodal crossing; it is scaled to 1 at the top of the atmosphere. It is known that D is not the closest a particle will approach Earth, especially in the case of streams associated with low inclination comets. In the case of streams associated with high inclination comets, however, the difference between D and the actual closest approach distance is inconsequential. Thus the IP is valid for streams with large orbital inclinations, as is the case for the Leonids and the Perseids.

2.2. INPUTS

In modeling the Leonids it was necessary to simulate ejection from comet Tempel-Tuttle during the last 12 revolutions, epochs 1600–1965. Three hundred thousand particles were ejected during each epoch, in both ejection schemes, for a total of 3.6 million particles for each case, Timestep and Perihelion. The meteoroid production rate was varied with the heliocentric distance as r_h^{-5} , based on previous simulations, and β ranged from $\sim 10^{-5}$ to 10^{-2} , resulting in a mass range between approximately $1 \mu\text{g}$ and 1 kg , as the density was assumed to be 1000 kg m^{-3} . A cap angle of $\alpha = 30^\circ$ was chosen. The radius of the comet was assumed to be 2.0 km (Hainaut et al., 1998).

For each ejection case and two different cap angles, comet Swift-Tuttle was modeled with 900,000 particles ejected over each of its last 9 revolutions dating from 826 to 1862. This resulted in 4 total Perseid cases with 8.1 million particles each. Particle production depended on r_h^{-6} (Fomenkova et al., 1995). Again, β ranged from $\sim 10^{-5}$ to 10^{-2} , the corresponding masses from 1 kg down to $1 \mu\text{g}$, assuming density was 1000 kg m^{-3} . Cap angles of 25° and 60° were chosen based on the literature, respectively Jones (1995), and Jones and Brown (1996a) and Brown and Jones (1998). The radius of the comet was assumed to be 11.0 km , based on Boehnhardt et al. (1996).

2.3. MODEL COMPARISON

Per Welch (2003), numerical simulations of meteor showers tend to conform to one of two types whereby: (1) large numbers of meteoroids are ejected from a parent comet and the subsequent evolution of these particles is followed until the period of interest, or (2) the meteoroid orbit with the

correct change of period necessary to pass through the relevant node at the time of the shower in a given year is determined for a given ejection epoch. The MSFC model is of the first type. It is similar to models seen in Brown (1999), Brown and Arlt (2000), Göckel and Jehn (2000), and Vaubaillon and Colas (2002) in that respect. The models in Kondrat'eva and Reznikov (1985), Wu and Williams (1996), Asher (1999), and McNaught and Asher (1999) are of the second type. Welch (2003) is a combination of these types. It is unknown at this time under which type category the work of Lyytinen (1999) and Lyytinen and Van Flandern (2004) falls.

A brief summary comparing the Leonid MSFC model to the Leonid models of other authors is given in Table I. The main categories of comparison involve how the cometary ephemerides are created, the ejection velocity law used, the particle production dependence on heliocentric distance, the ejection scheme – particles ejected along the comet's orbit or only at perihelion, and the integrator used to integrate the position of the comets back in time and/or evolve the particles forward in time. The MSFC model uses JPL Horizons to calculate the cometary ephemerides, instead of introducing the additional complexity of integrating the comets, whose dynamics are significantly influenced by jetting, reflected in the A1 and A2 terms. Ejection velocity is based on Jones and Brown (1996b) and Jones (1995). Type 1 models, with the exception of Vaubaillon and Colas (2002), and Welch (2003) have explored this ejection velocity model, among others, with a set cap angle of 60° . Vaubaillon and Colas (2002) and Welch (2003) have investigated the ejection velocity model of Crifo and Rodionov (1997). The MSFC model's particle production dependence on heliocentric distance is not fixed at r_h^{-2} but is instead based on observational evidence found in the literature or determined based on previous simulations. Two different ejection schemes are compared in this model: particle ejection along the comet's orbit within 2.5 AU and also ejection just at the hour of perihelion, like models of Types 1 and 2. In the MSFC model a 4th order variable step-size Runge–Kutta integrator is used to evolve the particle orbits, like Brown (1999), and Brown and Arlt (2000). Various other numerical integrators have been used, including Runge–Kutta–Nystrom 12 (10) 17 (e.g. Welch, 2003), Radau 15 (e.g. Vaubaillon and Colas, 2002), and Stumpff–Weiss (e.g. Göckel and Jehn, 2000).

3. Results and Discussion

A subset of the total number of particles propagated, those extracted within 0.01 AU of Earth within 1 week before and after the expected shower peaks of interest, is now examined. As stated previously, an IP is computed for each particle of this set approaching the Earth. In effect, this is the scaled

probability that the particle will hit Earth. (It must be noted that a stream that approaches Earth, but does not appear to cross its path, still has a nonzero probability of striking the Earth.)

The particle IPs are summed in 0.01° solar longitude bins (this corresponds to a time interval of 14.6 min), thereby representing cumulative probabilities. Ideally, the IPs would be summed in 0.005° bins, corresponding to the Earth moving approximately 1 Earth diameter plus the height of the atmosphere. There were not enough particles in the subset, however, for this binning scheme, so 0.01° solar longitude bins were used.

A Lorentzian is fit to the binned IP versus solar longitude – essentially the flux profile – in order to determine the time of the shower peak. The results are compared to observations of the 1998 and 1999 Leonid showers, and the 1993 and 2004 Perseids. In this way, the goal – to compare the solar longitudes of the main shower peak resulting from the model with observations of past Leonid and Perseid encounters, thereby validating the MSFC meteoroid stream model's timing – is achieved.

In the following sections the results of this validation are described. Cross-section plots showing the composition of the showers by stream are included and appear as parts (a) of Figures 1–4. Each of the particles in parts (a) has an associated IP. These IPs are summed in solar longitude bins and, for comparison purposes the amplitudes are scaled, thus creating a flux profile, shown in parts (b) of Figures 1–4. The model results are simply scaled to the peak ZHR observed so that the *time* of the observed peak and that of the peak predicted by the model can be easily compared. The observational data is also shown in parts (b). Finally, predictions from other modelers, where possible, are given in tabular form.

3.1. LEONIDS

Figure 1 shows the modeling results of the 1998 Leonids. The shower had two main peaks. The first peak, thought to be characterized by old ejecta according to Arlt and Brown (1999), was not modeled. The second peak (the nodal peak), however, is clearly prominent at solar longitude $235.311^\circ \pm 0.007^\circ$ (ibid). It is made up of particles ejected from recent passages of Tempel-Tuttle, namely 1965, 1932, and 1899. The MSFC model predicted a peak time at $235.27^\circ \pm 0.01^\circ$, a difference of about 1 h. Table II summarizes the results of the 1998 Leonid encounter alongside predictions from other authors.

The 1999 Leonid result can be seen in Figure 2. A storm of activity was observed at $235.285^\circ \pm 0.001^\circ$ (Arlt et al., 1999). The MSFC model predicted the storm peak, consisting mainly of particles from 1899 to 1932 but

TABLE I
A brief summary comparing the Leonid MSFC model to the Leonid models of other authors

Authors (Leonids)	Cometary elements/ Ephemerides source	Ejection velocity	Particle production dependence	Ejection scheme	Integrator
MSFC	JPL Horizons	Jones ejection (Jones, 1995; Jones and Brown, 1996b)	r_h^{-5}	Timestep, within 2.5 AU; Perihelion	Runge-Kutta 4
Brown (1999), Brown and Arlt (2000)	Yeomans et al. (1996)	Jones ejection (Jones, 1995), modified Jones and parabolic Jones (Brown and Jones, 1998), Crifo (1995)	r_h^{-2}	Timestep, within 4 AU	Runge-Kutta 4
Göckel and Jehn (2000)	–	Jones ejection (Jones, 1995), modified Jones and parabolic Jones (Brown and Jones, 1998), Crifo (1995)	r^0	Timestep, within 4 AU	Stumpff-Weiss
Vaubailon and Colas (2002)	Rocher (2002)	Crifo and Rodionov (1997)	r^0 , weighted later by r_h^{-2}	Timestep, within 3 AU	Radau 15
Kondrat'eva and Reznikov (1985)	independent	set at 1 value at perihelion – 0 km/s – then iteratively determined	n/a	Perihelion	algorithm of Kulikov (1960)
Wu & Williams (1996)	n/a	set at 1 value at perihelion – a mean ejection velocity less than 0.6 km/s	n/a	Perihelion	Runge-Kutta– Nystrom

Asher (1999), McNaught and Asher (1999)	Nakano (1998), Yeomans et al. (1996)	n/a	n/a	Perihelion	Radau 15
Welch (2003)	Nakano (1998)	Jones ejection (Jones, 1995), modified Jones (Browm and Jones, 1998), Crifo and Rodionov (1997)	r_h^{-2}	Timestep, within 3.5 AU	Runge-Kutta-Nystrom

The main categories of comparison involve how the cometary ephemerides are created (most modelers take cometary elements from various sources and integrate backwards), the ejection velocity law used, the particle production dependence on heliocentric distance, the ejection scheme – particles ejected along the comet’s orbit or only at perihelion, and the integrator used to integrate the position of the comets back in time and/or evolve the particles forward in time. The top section of the table shows models of Type 1, the middle section shows models of Type 2, and the bottom section shows the hybrid. It is unknown at this time under which type category the work of Lyytinen (1999) and Lyytinen and Van Flandern (2004) falls; these works are not included in this table.

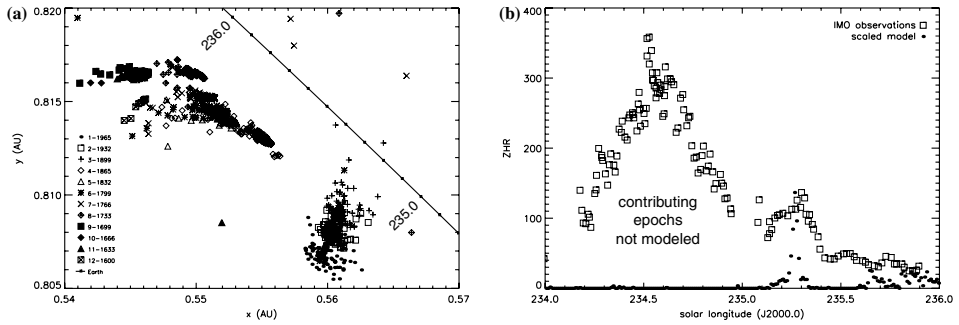


Figure 1. Results of the 1998 Leonids, Timestep case. (a) Cross-section in $x - y$ ecliptic coordinates showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. Ejecta from 1899, 1932, and 1965 played the greatest role in the nodal peak. (b) Comparing the scaled model with observations. Observational data was collected by the International Meteor Organization (IMO) and published in Arlt and Brown (1999). The model is scaled to the maximum ZHR of the nodal peak.

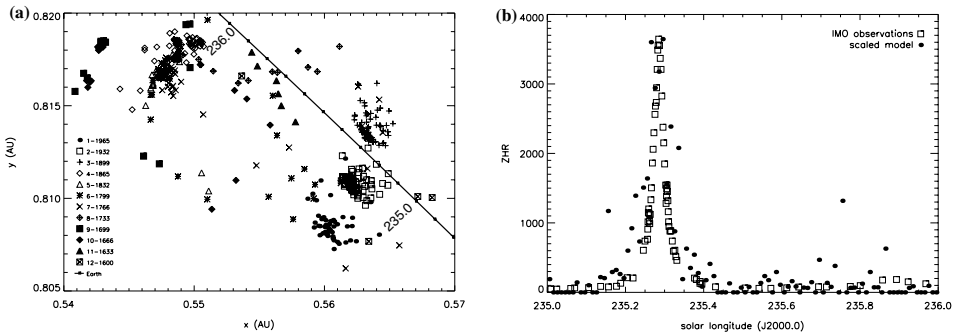


Figure 2. Results of the 1999 Leonids, Timestep case. (a) $X - Y$ cross-section plot showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. Revs 2 (1932) and 3 (1899) played the greatest role in the storm peak, as well as particles from 1965. (b) Comparing the scaled model with observations. Observational data was collected by the IMO and published in Arlt et al. (1999).

also including those from 1965, at $235.282^\circ \pm 0.002^\circ$. This is a difference of just over 4 min. The MSFC results for the 1999 Leonids, and the results of other authors, are presented in Table III.

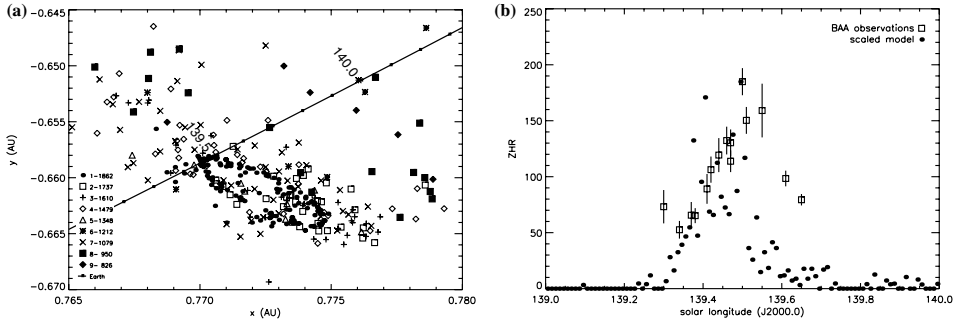


Figure 3. Results of the 1993 Perseids, Timestep case, 60° cap angle. (a) Cross-section in $x - y$ ecliptic coordinates showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. Ejecta from years 1862, 1479, and 1610 made up the bulk of the peak, with 1862 being most prominent. (b) Comparing the scaled model with observations. Observational data was collected by the British Astronomical Association (BAA) and published in Bone and Evans (1996).

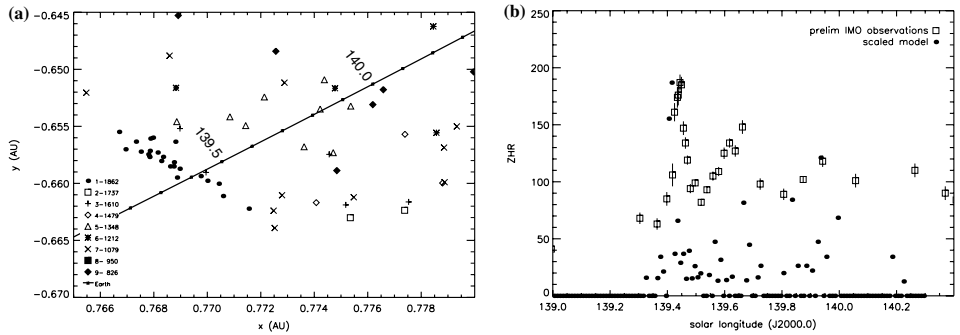


Figure 4. Results of the 2004 Perseids, Timestep case, 60° cap angle. (a) $X - Y$ cross-section plot showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. The maximum was made up from the 1862 stream. (b) Comparing the scaled model with observations. Observational data was collected by the IMO, and is not yet published (Arlt, unpublished observations).

3.2. PERSEIDS

Figure 3 illustrates the modeling results of the 1993 Perseids. The main peak occurred at $139.53^\circ \pm 0.01^\circ$ (Bone and Evans, 1996; Rendtel and Brown, 1997). A time of $139.491^\circ \pm 0.002^\circ$ was determined from the MSFC model, a

TABLE II

This table shows the modeling results of various authors alongside the results of the MSFC model and the observations for the 1998 Leonids

Year	Peak	McNaught and Asher (1999)	Brown and Arlt (2000)	MSFC result	Observations	MSFC difference
1998	Nodal	–	–	235.265	235.311	~1.1 h
	1965	235.26	235.34	235.262	<i>n/a</i>	<i>n/a</i>
	1932	235.27	235.22	235.263	<i>n/a</i>	<i>n/a</i>
	1899	–	–	235.270	<i>n/a</i>	<i>n/a</i>

The activity peak near the passage of the descending node of Tempel-Tuttle is referred to as the nodal peak; the fireball peak made up of older ejecta was not modeled. Modeling by McNaught and Asher (1999) and Brown and Arlt (2000) found that the 1965 and 1932 streams contributed to the nodal peak and calculated separate solar longitudes for each. Binning the IPs of ejecta from different epochs separately and fitting a curve to the data, the solar longitudes of the maxima for 1965 and 1932 ejecta from the MSFC model are shown for comparison purposes. Material from 1899 was also found to be a contributor and shown accordingly. Observations showed a peak at solar longitude 235.311 (Arlt and Brown, 1999). An analysis of the subset described in the text, combining ejecta from each perihelion passage (1965, 1932, and 1899 included) gives a peak at 235.265, a difference of about an hour. Errors are omitted for convenience.

TABLE III

This table shows the modeling results of various authors alongside the results of the MSFC model and the observations for the 1999 Leonids

Year	Peak	Kondrat’eva and Reznikov (1985)	McNaught and Asher (1999)	Brown (1999)	Lyytinen (1999)	MSFC result	Observations	MSFC difference
1999	Storm	–	See 1899	See 1899	See 1899	235.282	235.285	~4 min
	1965	–	235.279	–	–	235.272	<i>n/a</i>	<i>n/a</i>
	1932	–	235.273	–	235.270	235.275	<i>n/a</i>	<i>n/a</i>
	1899	235.29	235.29	235.3	235.291	235.295	<i>n/a</i>	<i>n/a</i>

A storm of activity was observed at solar longitude 235.285 (Arlt et al., 1999). In the models of Kondrat’eva and Reznikov (1985), McNaught and Asher (1999), Brown (1999), and Lyytinen (1999), as well as the MSFC model, the major (or only) contribution to the storm peak came from particles ejected in 1899. Solar longitudes of the maxima for material ejected in 1899, 1932, and 1965 are given separately. Binning the IPs of ejecta from different epochs individually and fitting a curve to the data, the solar longitudes of the maxima for the 1899–1965 streams from the MSFC model are shown for comparison purposes. An analysis of the subset described in the text, combining ejecta from each perihelion passage (1965, 1932, and 1899 included) gives a storm peak at 235.282, a difference of about 4 min. Errors are omitted for convenience.

difference of 57 min. Particles ejected from Swift-Tuttle’s passages in 1862, 1479, and 1610 were the main contributors. This breakdown is somewhat different from Brown (1999). The 1862 stream contributed the most significantly.

TABLE IV

This table shows the modeling results the MSFC model, alongside the results of Lyytinen and Van Flandern (2004) where possible, and the observations for the 1993 and 2004 Perseids

Year	Lyytinen and Van Flandern (2004)	MSFC result	Observations	MSFC difference	Main contributors
1993	–	139.491	139.53	~57 min	1862, 1479, 1610
2004	139.441	139.42	139.443	~34 min	1862

The main peak of the 1993 Leonids was at 139.53 (Bone and Evans, 1996; Rendtel and Brown, 1997). The MSFC model showed a peak at 139.491, a difference of about 57 min. Particles ejected from Swift-Tuttle's passages in 1862, 1479, and 1610 were the main contributors. In 2004, material from 1862 was the main contributor to the peak. The prediction of Lyytinen and Van Flandern (2004) was very close to what was observed. The result of the MSFC model, with a peak at 139.42, was about 34 min premature. Errors are again omitted for convenience.

The 2004 Perseid result is shown in Figure 4. The maximum occurred at $139.443^\circ \pm 0.003^\circ$ (Arlt, unpublished observations). The MSFC model predicted a peak time of $139.42^\circ \pm 0.01^\circ$, a difference of 34 min. Particles from 1862 made up the peak.

Table IV summarizes the results of the Perseid encounters.

3.3. MODEL VARIABLES

Two different ejection cases, Timestep and Perihelion, were simulated for both the Leonids and the Perseids. In general, the Perihelion case produces narrower particle distributions, as is to be expected. An example of this can be seen for the 2000 Leonids in Figure 5(a). These two cases yield similar peak times at this preliminary analysis stage. It is the Timestep case, however, that is felt to be more physically realistic.

The Leonids were only simulated with one cap angle value. For the Perseids, two different cap angles, $\alpha = 25^\circ$ and $\alpha = 60^\circ$, were tested. The smaller of the two values simulates an exit cone of about 60° ; the 60° cap angle corresponds to a hemispherical exit cone (Jones and Brown, 1996b). Of the two values, the 60° cap angle model generally predicts a solar longitude closer to that of the observed maximum ZHR. The 1998 Perseids, shown in Figure 5(b), is a good example of this. With scaling, the maximum is clearly distinguishable despite the scatter. The observed peak ZHR occurred at solar longitude $139.75^\circ \pm 0.03^\circ$ (Arlt, 1999). The 60° and 25° cap angle models have peaks at $139.72^\circ \pm 0.01^\circ$ and $139.83^\circ \pm 0.01^\circ$, respectively.

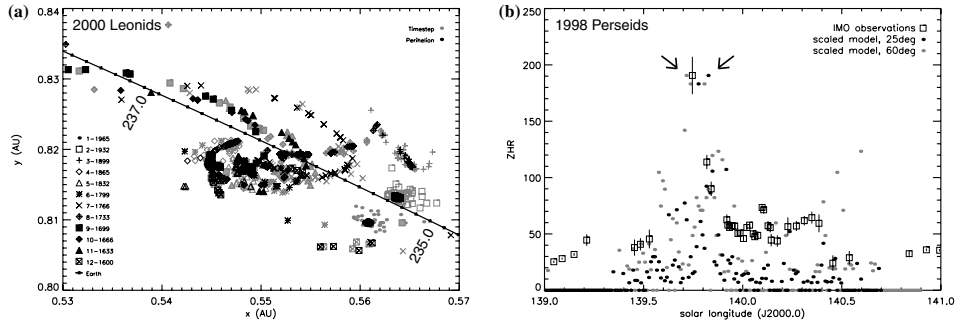


Figure 5. (a) $X - Y$ cross-section plot showing the composition of the shower by stream for the 2000 Leonids. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. The Perihelion ejection case (in black) is shown superimposed on the Timestep case (in gray). Note especially how focused the 1965 and 1932 streams of the Perihelion case are, as compared to the Timestep case. (b) Comparing two scaled models with observations for the 1998 Perseids. The 60° cap angle model (in gray) matches the time of the observed maximum better than the 25° model (in black). Observational data was collected by the IMO and published in Arlt (1999).

4. Summary

The MSFC stream model predicts, within about an hour or better, the peak times of several Leonid and Perseid encounters. Further refinement is necessary in analyzing the results, especially concerning ZHR calculations. Work exploring the effects of ejection schemes, the Timestep case and the Perihelion case, and cap angles is underway. Additionally, the inclusion of observational data, such as population indices, is underway in order to better constrain parameters associated with particle ejection from comets. Future work addressing the effects of different cometary ephemerides is planned; these effects are expected to be significant.

Acknowledgements

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MICROSHOWER STRUCTURE OF THE METEOR COMPLEX

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Abstract. Meteor radar observations of ionized trails in the Earth's atmosphere provide observations that do not depend on weather conditions and time of day and provide good statistics for analysis. Further development in the new quasitomographic analysis of the goniometric data of the Kazan meteoric radar has revealed a number of very weak meteoric streams with rates of more than 5–6 meteors per day. In addition to the known large meteor showers, we have found up to as many as 1000 small showers per month that we have named microshowers. We shall operationally define a microshower as the minimal meteoric stream which can be detected with the Kazan meteoric radar while quasitomographic procedures of processing interferometer data are used.

Keywords: Microshower structure, radar measurements, radiant coordinates

1. Introduction

Meteor radar observations of ionized trails in the Earth's atmosphere provide observations that do not depend on weather conditions and time of day and provide good statistics for analysis. Further development in the new quasitomographic analysis of the goniometric data of the Kazan meteoric radar has revealed a number of very weak meteoric streams with rates of more than 5–6 meteors per day (Sidorov and Kalabanov, 2001, 2003). In addition to the known large meteor showers, we have found up to as many as 1000 small showers per month that we have named *microshowers*. We shall operationally define a microshower as the minimal meteoric stream which can be detected with the Kazan meteoric radar while quasitomographic procedures of processing interferometer data are used.

Thus we take as a provisional and practical definition that a microshower is 5 or more meteors which are observed within 1 day having radiants at a discrete location on the celestial sphere. Each cell has a 2° by 2° angular dimension and contains statistically identical velocities within a 3 km/s velocity uncertainty. The corresponding spread in orbital elements of each group is a non-linear function determined by the coordinates and dimensions

of each resolution site and cannot be specified in general. This is not a disadvantage since tests for determining stream membership without conversion to orbital elements are now available in Valsecchi et al. (1999a); and Jopek and coworkers (1999b). Hence, in this context, a meteoric shower becomes a set of independently observed microshowers with closely located radiant coordinates and similar velocities. Microshower detection then becomes a non-linear procedure determined by choosing suitable thresholds. In general, thresholds are determined so that the possibility to detect false a shower would be always less than 5% (Sidorov and Kalabanov, 2001, 2003) and as such would give us a probability of detection of up to 10 times more than would a Poisson density of sporadic meteors with a uniform radiant distribution on celestial hemisphere. But we don't know *a priori* what the real distribution of sporadic radiants is. If the sporadic radiants have an irregular distribution, the observed microshowers are just the peaks of its irregularities. So what constitutes a peak irregularity? It is just a group of meteors with the equal velocities and equal radiant coordinates. Thus a microshower may be either a fragment of the sporadic background or a fragment of a meteor shower without distinguishing them in an operational sense. In order to represent microstreams from an astronomical point of view requires converting the data to orbital elements' which is not done here.

2. Distribution of Microshower Radiants on Celestial Sphere

In Figure 1, the general distribution of radiants of 2802 microstreams on celestial sphere for 1 month (August 1986) of radar observation is shown. Here we present microshowers with more than 5 meteors per day. The coordinate system is centered on the apex with the x -axis proportional to the

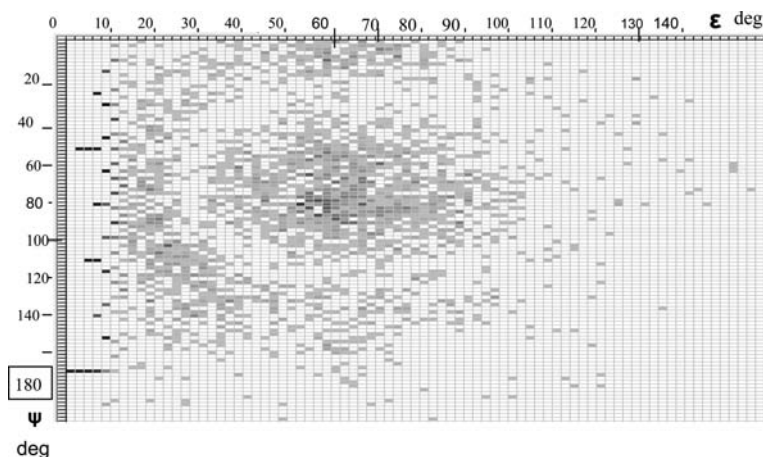


Figure 1. Microshower radiant distribution on celestial sphere in August 1986.

elongation angle of the radiant from apex and the y -axis is proportional to the ecliptic longitude of the radiant, where angles in the range 180° – 360° correspond to southern hemisphere radiants. The number of meteors registered in each microshower is determined by the degree of shading. The original database also contains parameters of orbits of all individual meteors included in a specific microshower, but these are not discussed here.

There are no large meteor showers in this month except the Perseids. But usually meteors at the velocities of the Perseids are hard to observe by the radar diffraction method (Voloshchuk et al., 1989). Since velocity measurements are a required component in our analysis method, this known velocity bias means we did not observe the Perseids as a large shower.

The shower with the most activity (and NOT the Perseids) was observed from August 11 to August 25 with maximum rate on August 15 ($N=34$ meteors per day), and with coordinates $\alpha=52^\circ$, $\delta=23^\circ$ ($\varepsilon=5^\circ$, $\psi=59^\circ$). The areas of activity of this shower are indicated with arrows. August is a month with active microshowers but all lacking a common origin. In the Figure 1, we can see ring structures in the distribution of the number of microshowers on the celestial sphere. Areas of maximum radar sensitivity near the horizon and areas near the zenith where the radar is insensitive, all move on the celestial sphere owing to the Earth's rotation. In addition, it is possible to see an area of increased number of microshowers in the central part of the map, where radiants are not near the horizon. In Sidorov et al. (2004), we showed for one December period a ring-like distribution of Kazan radar sensitivity on the celestial sphere which is apparently related to the structure in Figure 1. The structures seem to be an effect of the Earth's rotation resulting from the radar sensitivity pattern moving on the celestial sphere. Finally, it is possible to see a reduction of microshower density in the right part of map, near the antiapex, obviously, connected with a reduction of radar sensitivity to meteors having velocities less than 20 km/s.

All this is very similar to the distribution of sporadic meteors on the celestial sphere obtained by other methods (Voloshchuk et al., 1989).

It is interesting, furthermore, to see how the most active microshowers are distributed on the celestial sphere. For this we increased the specified threshold up to 8 meteor per day for the same date (Figure 2).

With this change of threshold, the total number of detected microshowers falls from 2802 to 272. This map shows some of the same properties in common with the distribution in Figure 1 but with more irregularities. By the same token, microstreams would seem by their nature and definition to be an unusual occurrence. If one looks at this map on different days and in a narrower interval of velocities, it is possible to see that sometimes, in the narrow velocity intervals only single microshowers are visible, and sometimes microshowers are almost absent.

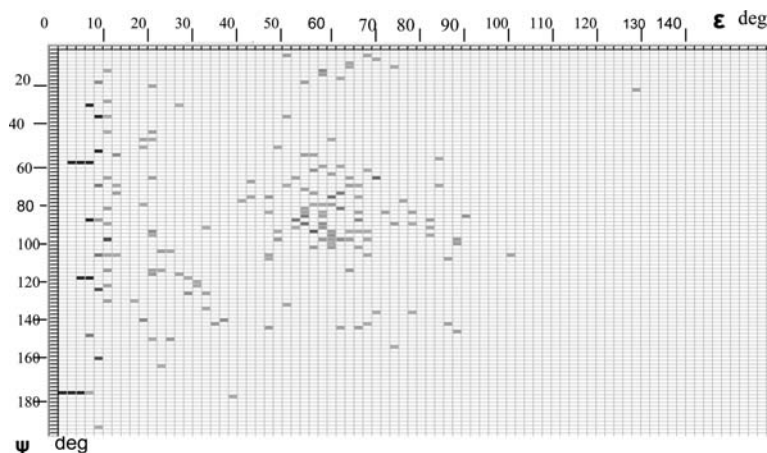


Figure 2. Radiant distribution of microshowers on celestial sphere in August 1986 (meteor number in microshower is more than 8 meteors per day).

In Figure 3, an example of the 43 microshowers, distribution detected in August 19, with a velocity interval of 41 ± 2 km/s is shown. It is seen that radiants of 34 microshowers are casually present on the celestial sphere but nine from the sample form an association with small angular dimension.

In some cases, it is possible to observe close associations of microshowers consisting of 10 and more microshowers acting simultaneously in a small part of the celestial sphere. Thus in the two-day period, June 29–30, 1986 (Figure 4) we see 23 microstreams, 18 of which have formed close associations in

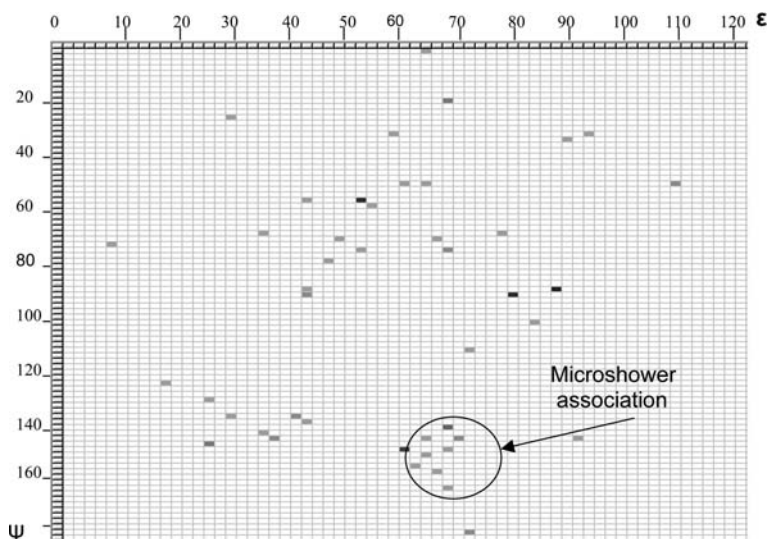


Figure 3. Partial microshower radiant distribution, August 19, $V = 42 \pm 2$ km/s.

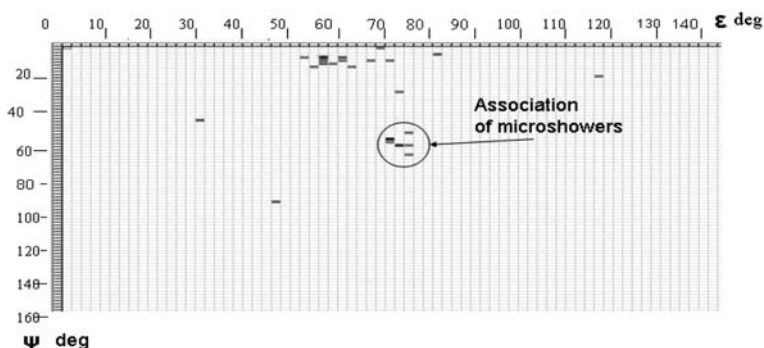


Figure 4. Microshower distribution, June 29–30, 1986, $V = 39 \pm 2$ km/s.

near $\varepsilon = 60^\circ$, $\psi = 8^\circ$, another in a vicinity $\varepsilon = 70^\circ$, $\psi = 74^\circ$. In the first case, this association is near to the region of the Arietids radiant, though at this time the shower is several days past its quoted activity range. In the second case, the association is not connected to any known regular shower.

Therefore it is concluded that microshowers represent the meteoric complex as a whole, representing both a shower and a sporadic meteor population.

3. Dependence of Microshower Rate on Threshold Level

The first consideration, naturally, is that the majority of microshowers depends on the threshold. It is interesting to know how microshowers, which are small showers, can represent sporadic background.

Let us have sporadic background of given density. Background rate from discrete cell of celestial sphere is a random process as the result of fluctuations in arrival.

When the rate of this random process reaches (from below) the threshold level (which again is defined as the minimum number of meteors for a microshower detection), we can in fact detect that there is a microshower. Thus, we conclude that microshowers at threshold level are an irregular feature of background fluctuations.

If all meteors are sporadic, the number (N) of microshowers will reduce with increasing threshold level according to power relation of meteor mass variation and Poisson law distribution number of meteors in time interval (curve 1 in Figure 5). But if microshowers are small showers with a higher average rate in comparison with the background rate, the rule of changing of number of microshowers with threshold will be more sloping. In Figure 5, we show the dependence of $\log_2$ number of detected microshowers from threshold level for August 1986 (curve 2 in Figure 5). We can see that the relationship of changing $\log_2 N$ differs from the almost linear Poisson law

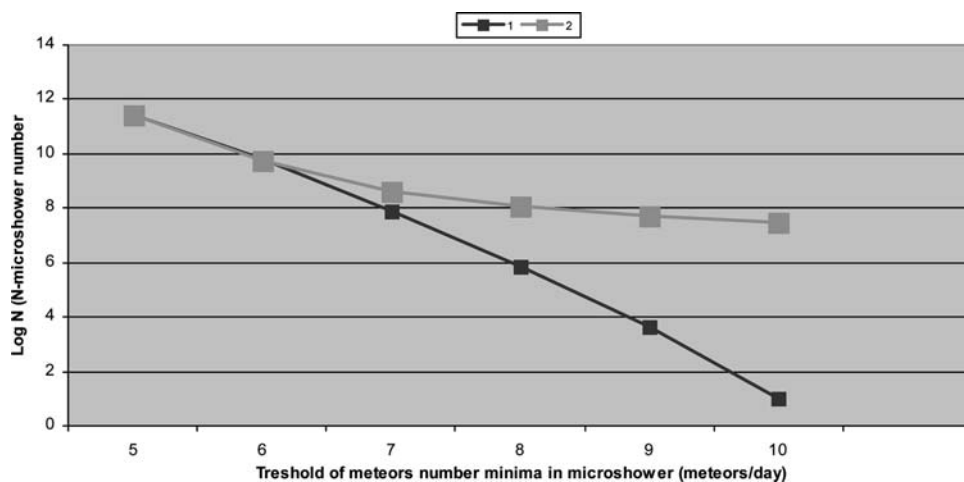


Figure 5. Dependence of log number of detected microshowers from threshold for August 1986.

dependence (curve 1) when the threshold is more than 8 meteors per day. The same type of behavior can be seen in June 1986 (Figure 6). The number of microshowers falls sharply with an increase of the threshold detection. Thus the general number of detected microstreams in June 1986 falls from 2078, at a threshold of 5 meteors/day in a microshower to 654 meteors at a threshold of 6 meteors/day (see Figure 3).

The usual showers, apparently, should differ from the sporadic ones in having a greater number and smaller dependence on a threshold. So at a threshold of 9 meteors for a day in June we observe 149 microstreams, at

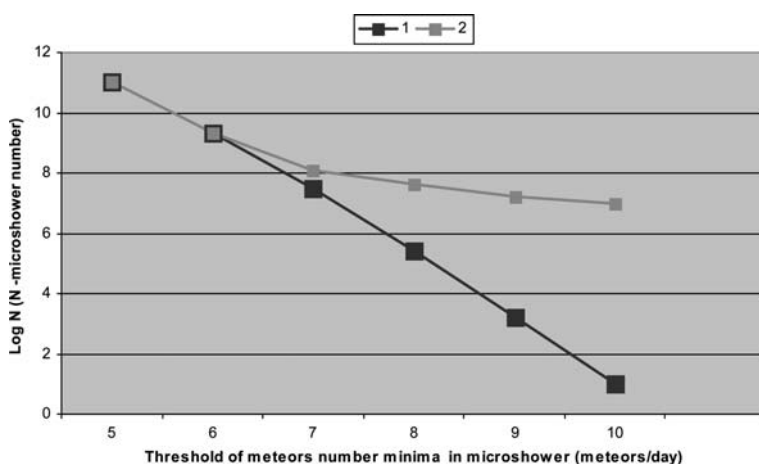


Figure 6. Dependence of $\log_2 N$ (number of microshowers) from microshowers threshold level for June 1986.

a threshold 10 we observe 126 microshowers. If all meteors were only sporadic, without that correlation, the dependence of the number of microshowers on a threshold level would be almost linear (look at curve 1 in figure 6) in logarithmic scale. It is not clear yet, at what threshold we shall observe only small showers, instead of a sporadic background. Here it is necessary to take into account, change of real sensitivity of the equipment for different sites of the celestial sphere and change of density of a sporadic background and exact enough definition of a small stream. Hence we somewhat arbitrarily decide that microshowers with rates more than 8 meteors per day be considered as a small showers rather than being sporadic background fluctuations.

4. Possible Explanation of Microshower as Real Measuring Object of Meteor Astronomy

It is possible to state (Sidorov et al., 2004) three concepts concerning the sources of these strongest microshowers which can be observed from the Earth:

- (a) These are the meteors of the sporadic background which has randomly fluctuated into microshowers. Perhaps such microshowers represent the intermediate part of the normal evolutionary transformation of old meteor streams into a smooth sporadic background.
- (b) These are dust traces of small comets or asteroids not yet found out by modern optical means although their orbits pass nearby to the orbit of the Earth. Above, we gave some evidence of a way to distinguish such microshowers from those microshowers of group (a) by changing the threshold for microshowers detection.
- (c) These are simply dust environments of very small asteroids or large meteorites which passed by near to the Earth or be dropped onto its surface at a time close to the appearance of microshowers.

In future, it would be interesting to actually compare the orbit parameters of the “larger” microstreams with the measured orbit parameters of meteoroids which have been observed to be dropped to Earth or with Near Earth Objects (NEOs) that have been recently discovered.

5. Microshower Radiant Associations

The congestion of microshowers with equal velocity (in limit of errors of measurement) and those closely located in radiant coordinates, we have named them as microshower associations. We also have noted (Sidorov et al., 2004)

that associations of microshowers accompany almost all known strong showers. Thus as an example of this, we have shown in Figure 4, a couple of the microshower radiants near the well-known daytime Arietid radiant. Such associations can be observed at all periods of activity of each main shower.

Besides those we can see microshower associations which act without observed known shower, but lasting an enough long time to establish its existence. A third type of *microshower association* occurs with even shorter lifetimes. The association in Figure 4 (lower) exists only 2 days.

Associations of microstreams also could occur through three mechanisms (Sidorov et al., 2004):

- (1) These are random groupings as a result of Poisson processes.
- (2) These are the concentrations of meteoric particles which have been pulled out from the older large meteoric streams by gravitational influence of planets, especially by Jupiter and scattered throughout the solar system, some of which cross the orbit of the Earth.
- (3) These are the concentrations of the meteoric particles which have been pulled out by the repeated gravitational influence of the Earth itself from the main distribution of an old large meteoric stream, whose orbit does not presently intersect the Earth directly and are scattered into the Earth's orbit.

In the second case, we can assume clusters of microshowers which the Earth will pass through consistently on an annual or other periodic basis. Thus velocities of some microshowers can change in time. In the third case, it is possible to determine the following properties, inherent in this mechanism:

- (1) Similarity of speeds of meteors inside a microshower, as a condition of its existence, long enough that it could be observed.
- (2) Identical coordinates ε , ψ for meteors inside a microshower, as consequence of presence of the common center of dispersion near to the Sun.
- (3) The span of activity of microshowers should correspond to span of activity of the basic shower, or, perhaps with fairly rapid dispersion a little bit more than the main shower.
- (4) Velocities of the microshowers which are included in associations should coincide within statistically uncertainty, as the gravitational field of the Earth at the moment of the maximal action is perpendicular to a direction of movement of meteors and changes only their direction, not their velocity.
- (5) Areas of a probable concentration of microshower radiants related to known shower radiants should repeat from year to year, while recurrence of occurrence of singular microshowers probably will be poorly repeating.

For each postulated source mentioned here, a computer filter is developed, allowing us to divide microstreams from different sources and to investigate their properties. So far, microshower with radiants close to Geminids satisfy all the listed properties. But we have many other associations which satisfy these properties.

6. Conclusions

Using a quasitomographic approach to the analysis of interferometric data from meteor radar, we have shown that a significant part of the influx of meteors occurs as discrete components which we have decided to call microshowers. We find that a significant part of the microshower population represents irregularities of the sporadic background. It seems that a significant part of a sporadic meteoric complex represents microstreams which can be discovered based on their collective properties.

The majority of associations of microshowers when grouped according to source, apparently, are from large meteoric streams which are not observed from the ground, but whose orbit approaches closely to the orbit of the Earth. Thus detection of microshowers, whose parameters may be measured by the radar method, enables us to receive some data about meteoric streams whose orbits which are not crossed by the Earth, but settle down close to it.

Apparently, many of the microstreams which have given birth to these microshowers present an intermediate stage of evolution of comet substances into the unstructured sporadic background and they are responsible for heterogeneity of angular distribution of radiants which are observed by classical meteor radars.

The simultaneous presence of many microshower associations in the vicinity of the Earth with identical velocities and small radiants indicates a significant role of the gravitational field of the Earth in the formation of the meteor flux falling on it. The orbits of microstreams which correspond to such associations have a common convergence point near Earth. If such associations also have common nature, the source of perturbation which births such association must be near the Earth. Historical repeated action of the gravitational field of the Earth may be one such source.

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ASSOCIATIONS OF METEOR MICROSHOWERS OR AS THE KAZAN RADAR “SEES” RADIANTS ON NORTHERN CELESTIAL HEMISPHERE

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Abstract. The discrete quasitomographic method of the analysis of the interferometric data of meteor radar gives us the possibility of measuring coordinates and velocities of very weak meteor showers with a 2×2 square degree resolution on the celestial sphere. The minimal rate of the meteors in each microstream is five meteors per day. At such sensitivity, basic distinctions between irregularities of the sporadic background and meteor streams vanish. More than 1000 of the detected microshowers per month are associated with a combination of (a) the large known meteor showers, (b) the weaker known meteor showers and (c) till now unknown associations of microshowers. All microshowers regardless of association have the identical velocities, limited areas of radiation and near simultaneity of their acting dates. The results are compiled as maps of radiant distribution and average velocities of microstreams for different months. From these it is possible to see how the microshower activity for various discrete sites on the celestial sphere correlate with the behavior of the well-known meteor streams and thus to infer the orbital properties of the different microstream configurations.

Keywords: meteor shower, radar measurements, celestial sphere, microshowers

1. Introduction

Meteor radars can supply data of meteor activity at any time of a day independently of weather but they suffer from low accuracy of orbit parameter measurements. The problem of increasing the accuracy of radiant measurements is especially acute for single station radars with an interferometer. Kazan meteor scientists for many years have been trying to solve the problem and now we present the main results. A feature of meteor stream is that the meteors belonging to it move on various orbits inside some bunch of orbits. The problem of distinguishing different orbit bunches of meteor streams and sporadic meteors is rather difficult. For

this purpose we used a mobile system of coordinates (ε , ψ) which is adhered to the Earth apex. A change of visible position of stream meteor radiants as result of the Earth crossing a bunch of stream orbits, is compensated by turn of coordinate system (ε , ψ) on the same angle. So a visible radiant position of meteors belonging to one stream does not vary in this coordinate system. Only the time of action distinguishes different orbits comprising a bunch of orbits of a meteor stream. Besides, the errors of measurement of a meteor velocity in this coordinate system does not change its visible coordinates. It is very essential for radar registrations since the error of velocity measurement is great.

2. Kazan Meteor Radar

Kazan meteor radar was specially constructed for research of the sporadic background and it was equipped with an interferometer using rotating antennas. The system has a 1 degree accuracy and uses a meteor velocity gauge based on the phenomenon of diffraction. The radar was taken into operation in 1975 with technical parameters given in Sidorov et al., (1979), Makarov et al., (1981) and other publications. The radar worked nonstop from 1986 to 1991 and intermittently up to 2002.

3. Quasitomographic Analysis

We started using a quasitomographic approach for our analysis of interferometer data with 10×10 square degree resolution for radiant coordinates and for 5–10 days of registration (Belkovich et al., (1991)). On Figure 1, there are two examples of the radiant distribution (1993, Sept. 1–10, resolution is 10×10 square degree) using two independent sets of observational data for quasitomographic process. Their similarity shows the reality of the feature but not artifacts of the noise.

Unexpectedly these maps have shown a sharp heterogeneity in the influx of sporadic meteors. On Figure 1 we can see maximum and minimum peaks as well as lack of any radiants. However the lack of the velocity data did not allow us to identify the observed patterns with known meteor streams.

To overcome this problem, both higher angular resolution and the availability of meteor velocities were required. To handle this new situation, we devised a new discrete quasitomographic solution for the interferometric data analysis.

4. Discrete Quasitomographic Analysis

The discrete solution starts with subdividing the celestial sphere into discrete cells with 2×2 square degree angular resolution. When five or more meteors are observed within 1 day with radiant positions in the same discrete cell, and with very similar velocities, we call this group of meteors as a *microshower*. A choice of the velocity interval equal to 3 km/s was made, as result of compromises between possibilities of diffraction method of velocity measurements and requirements of the tomographic method analyses (Sidorov and Kalabanov, 2001, 2003).

Part of meteors with a worst velocity accuracy are not included in minimum microshower group and considered as sporadic meteors.

Hereby, a meteor shower is a set of independently observed microshowers with closely located radiant coordinates and identical velocities. A microshower may be either a fragment of the sporadic background or a fragment of a known meteor shower.

5. Results of the Observations

In order to present a seasonal change of a visible microshower radiant distribution on the celestial sphere, we have shown here the experimental month maps of the radiant distribution for January, April, June, September and December. The month's data was better represented in years 1986 and 1994. The August map is presented in this issue (Kalabanov et al., in this issue [6]).

A partial distribution consisting of five microshowers per day in a 3 km/s velocity interval is shown on Figure 2. Four of them make up a close group which was observed only in one day.

In Figure 3, the distribution of all microshowers registered in January 1994 is shown. The degree of blackening in each cell is determined by the number of detected meteors. Our database itself contains meteor parameters for each cell. An arrow indicates the Quadrantids meteor shower. We can also see a ring-like structure of the increased sporadic radiant density as well as an area of increased microshower density near the Quadrantids radiant location. An enlarged image of the distribution of microshowers associated with the shower Quadrantids is shown on Figure 4. This demonstrates that we can examine the neighborhood of known meteor showers using this method.

In Figure 5, the distribution of microshowers on the celestial sphere for April 1986 is shown. A preference of meteor observations for the antiapex zone was noted, where meteor velocities are less than 20 km/s. But our radar like most of its type has poor sensitivity to the low velocity meteors. Therefore nearly half of the ring structures near the antiapex zone was not detectable. The well-known Lyrids meteor shower is indicated by an arrow.

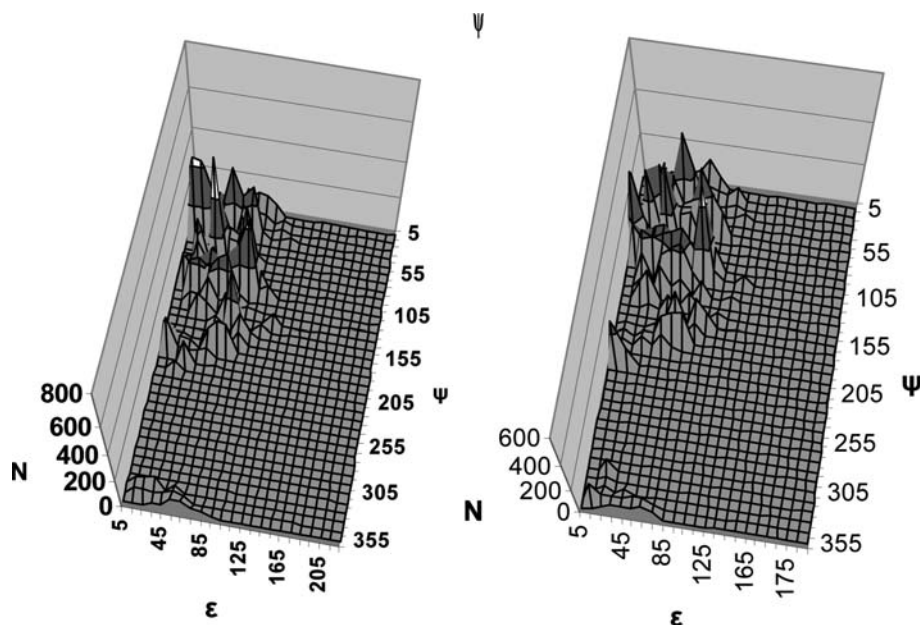


Figure 1. The examples of the quasitomographic radiant distribution (1993, Sept. 1–10, resolution 10×10 degree, two independent observational data sets).

In Figure 6, all microshowers of June 1986 are shown. Here the ring-like structure is almost completely visible. Note that the area of increased concentration of microshower radiants is nesting in the vicinity of the area of a

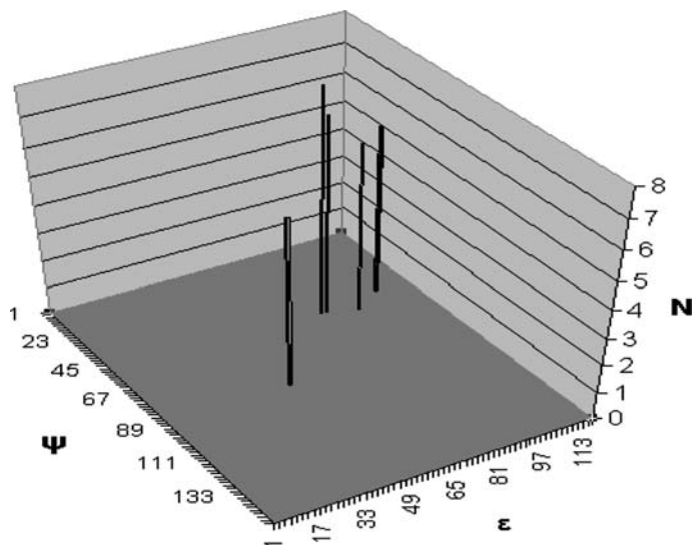


Figure 2. A microshower radiant distribution on the celestial sphere, May 21, 1986, $37 < V < 40$ km/s, apex coordinates (ϵ, ψ).

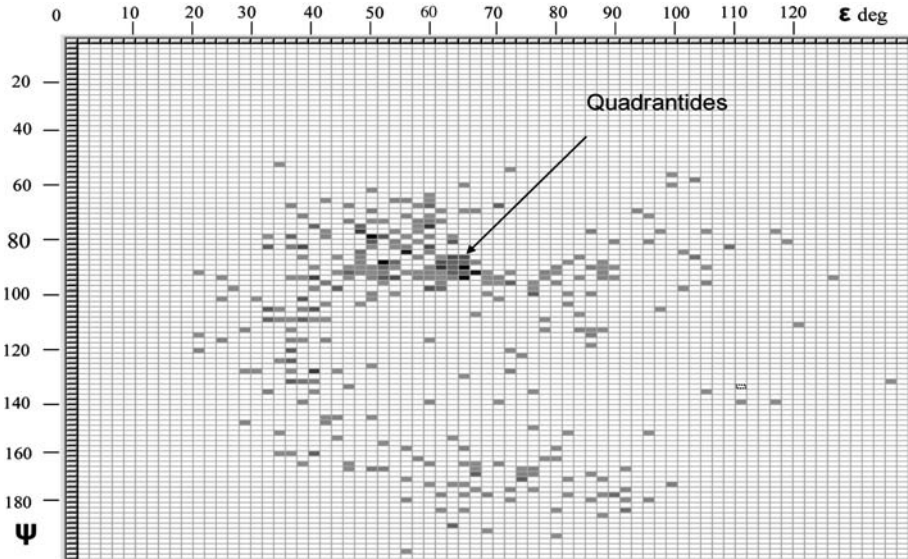


Figure 3. Distribution of microshowers, 1994 January (each cell 2×2 degree).

meteor shower day-time Arietids. It is interesting to compare this monthly distribution to those obtained for the same month in other years. In Figure 7, a distribution for June 1994 is given. Both figures (Figures 6 and 7) have a lot of similarities. However in 1994, an area of hyperactivity of microshowers in the right lower side of the figure was observed. It would be interesting to find out which event has produced such a difference.

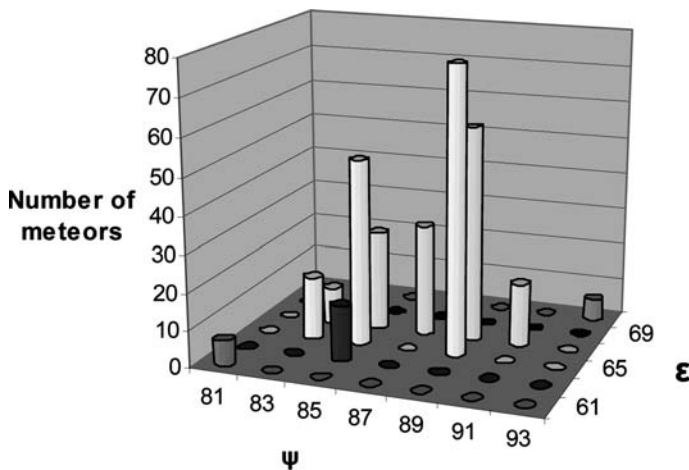


Figure 4. Distribution of microshower radiants identified to meteor shower Quadrantids in 1999.

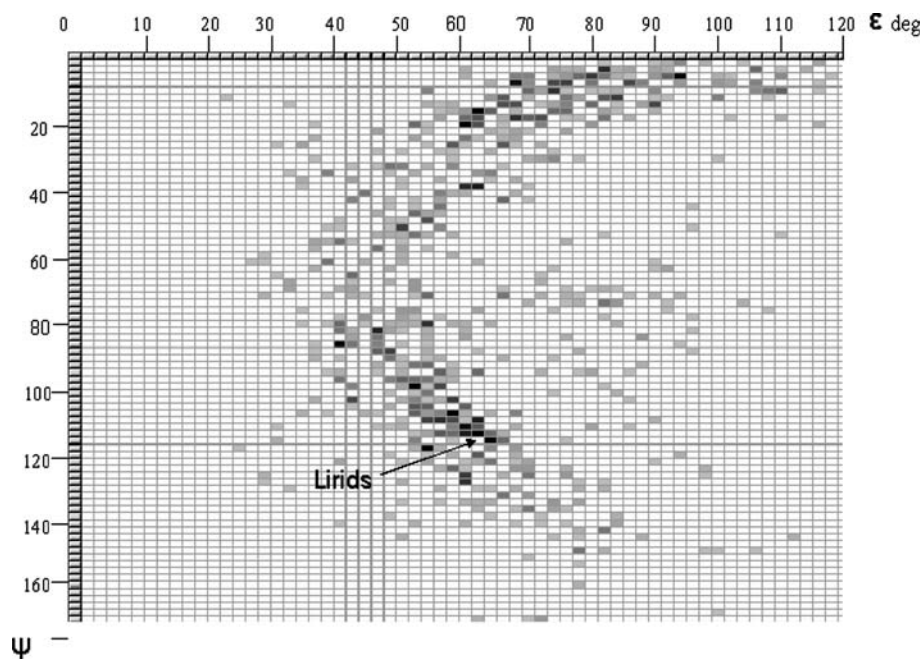


Figure 5. Distribution of microshower radiants in April, 1986.

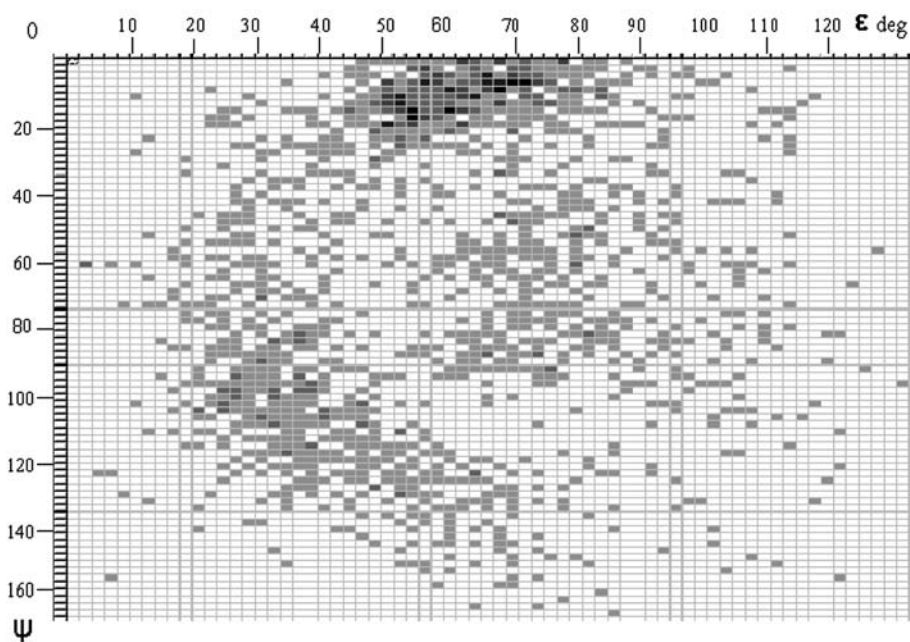


Figure 6. Distribution of microshower radiants in June 1986.

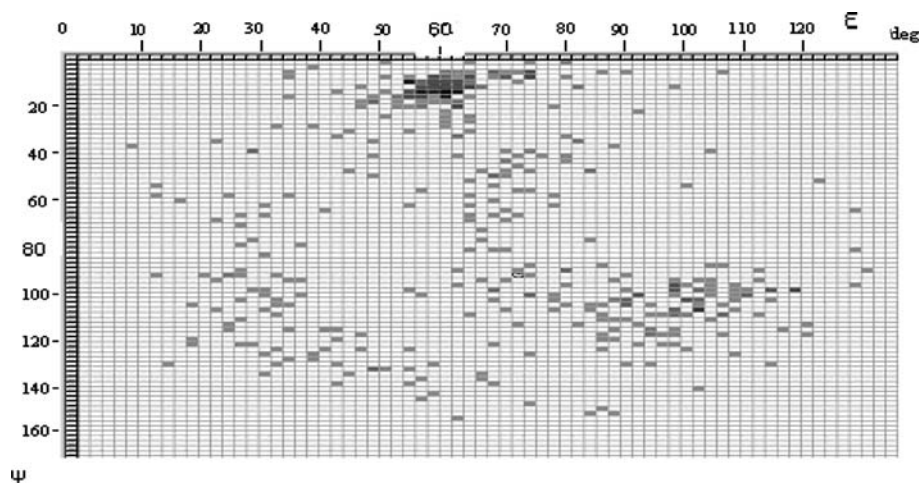


Figure 7. Distribution of microshower radiants in June 1994.

In Figure 8, an association of microshowers active on 1–2 June in 1994, with the velocity interval 31 ± 2 km/s is shown. This briefly appearing association contributes to the main observable differences between Figures 6 and 7.

In Figure 9, the distribution of microshowers for September 1994 is shown. An increased concentration of the microshowers in the apex and the central zones is observed. The microshowers on all other areas of the celestial sphere are distributed casually or form groups with the known large and

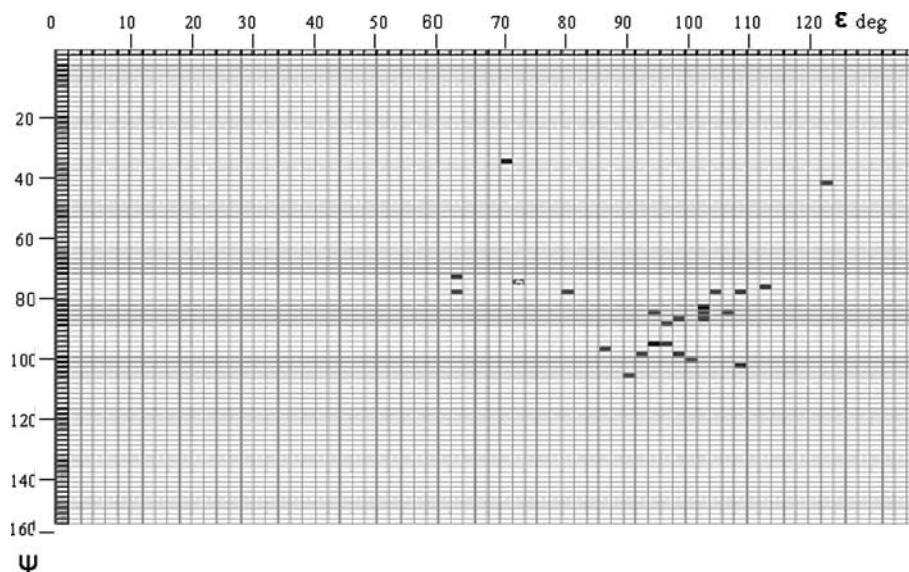


Figure 8. Distribution of microshower radiants on 1–2 June 1994, $V = 31$ km/s.

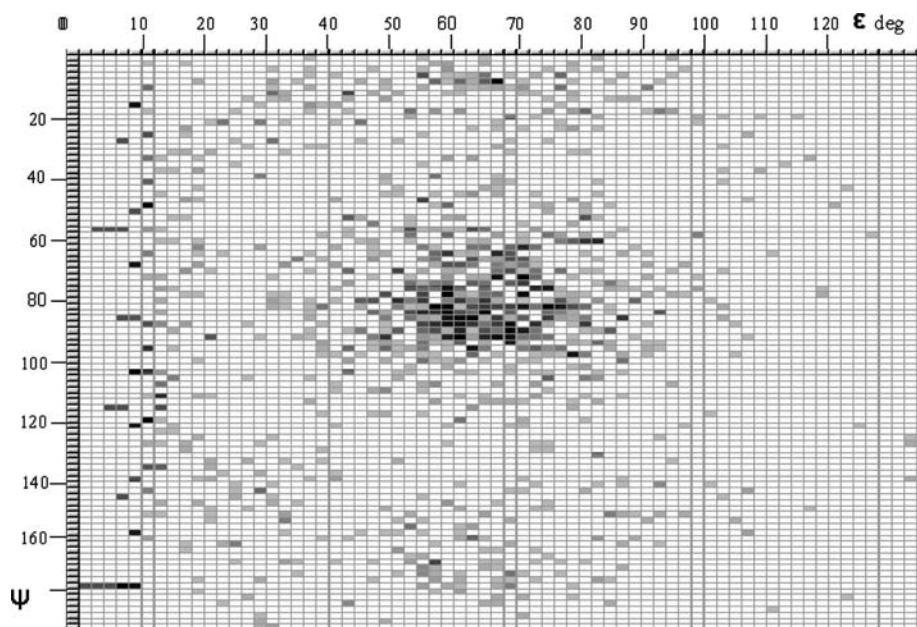


Figure 9. Distribution of microshower radiants in September 1993.

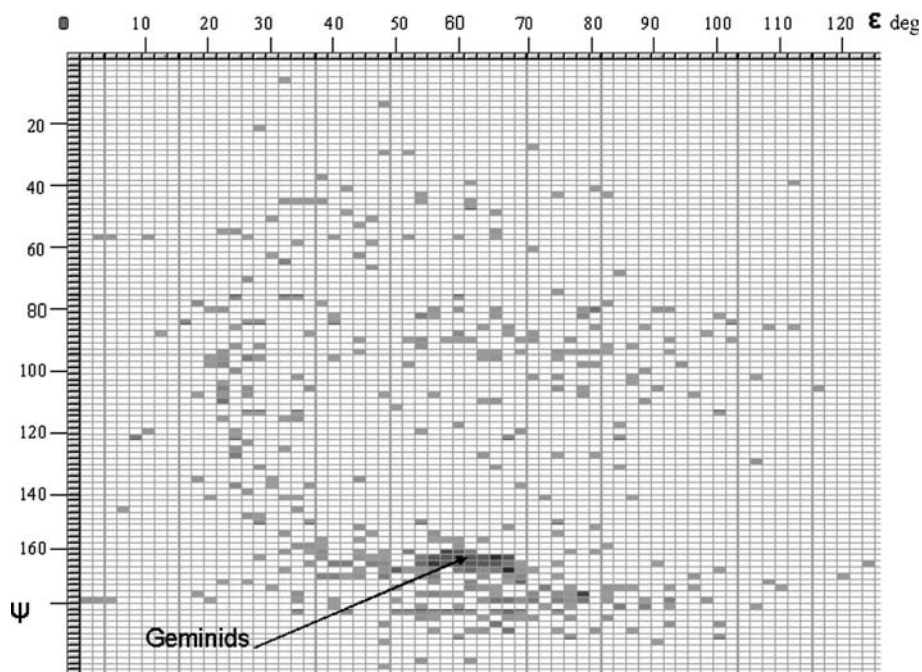


Figure 10. Distribution of microshower radiants, 1986 December 1–15.

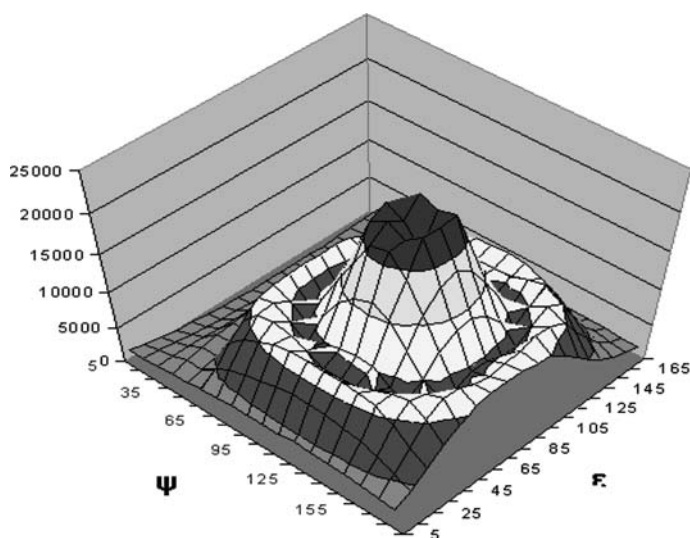


Figure 11. Distribution of the Kazan radar sensitivity on the celestial sphere on December.

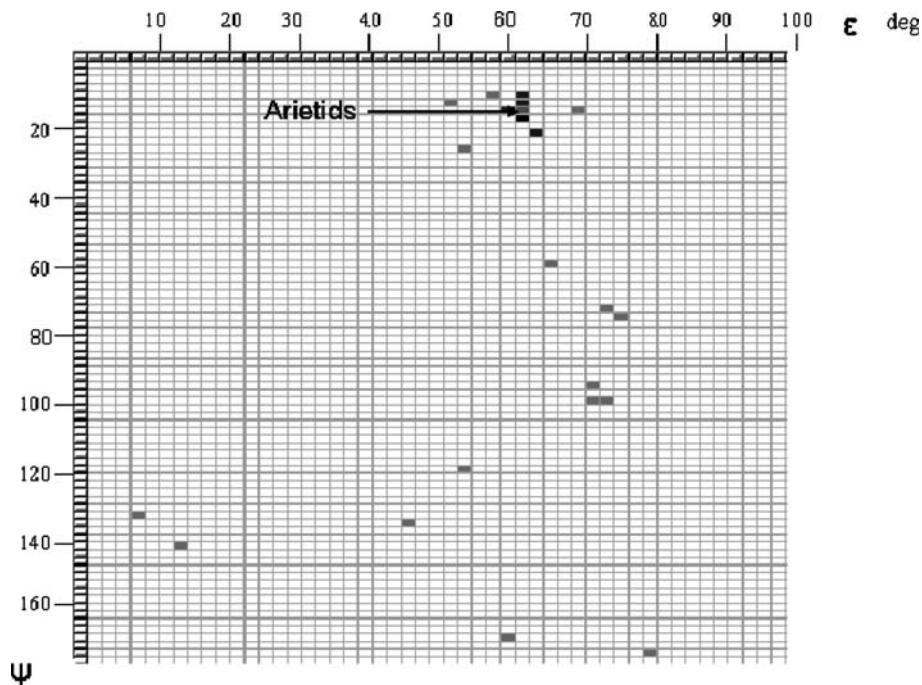


Figure 12. Microshower radiant distribution, June 3-4, 1986, $V = 36$ km/s.

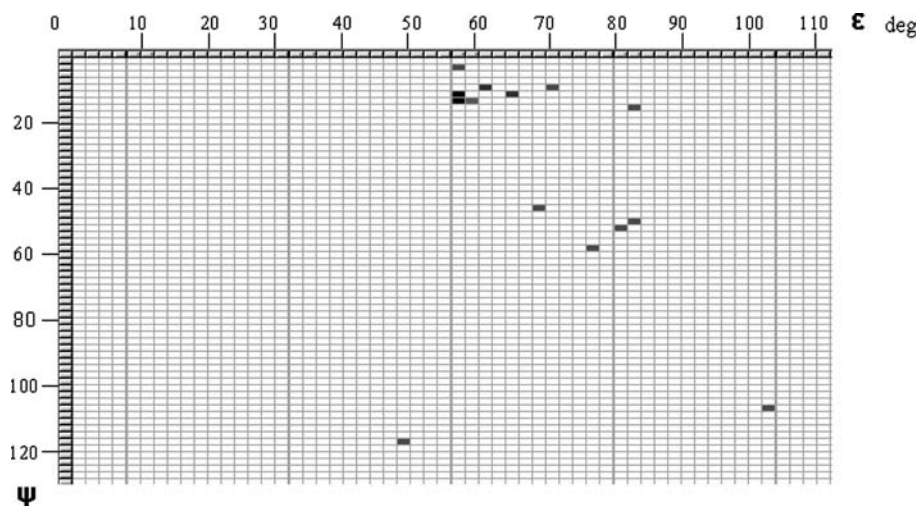


Figure 13. Microshower radiant distribution, June 5-6, 1986, $V = 36$ km/s.

small showers. Please note the increasing activity of microshowers near the apex zone.

In Figure 10, we present the distribution of microshower radiants on 1-15 December in 1986. Here it is possible to see the ring-like structures too. Again the arrow indicates an activity of the known shower Geminids. An increase in the number of the microshowers around the main Geminid shower is observed on all maps for other years. To explain the ring-like structures in all maps, we show on Figure 11 the hardware sensitivity of the Kazan radar on

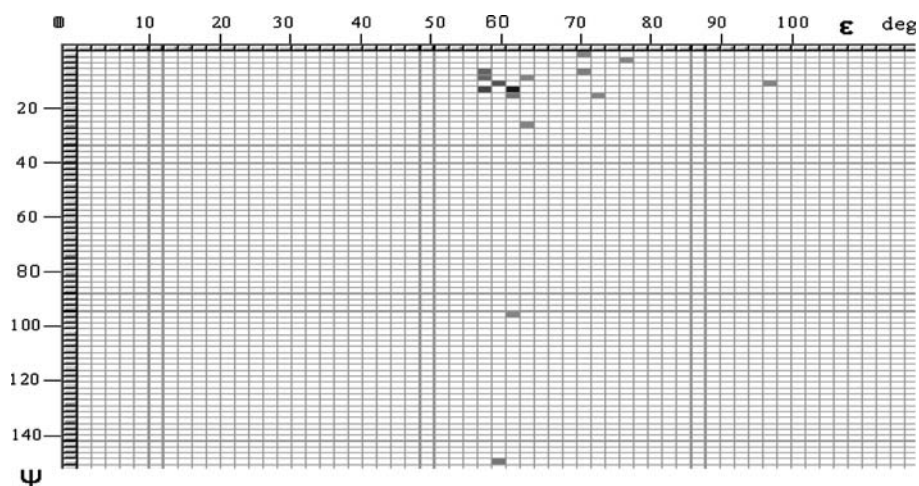


Figure 14. Microshower radiant distribution, June 7-8, 1986, $V = 36$ km/s.

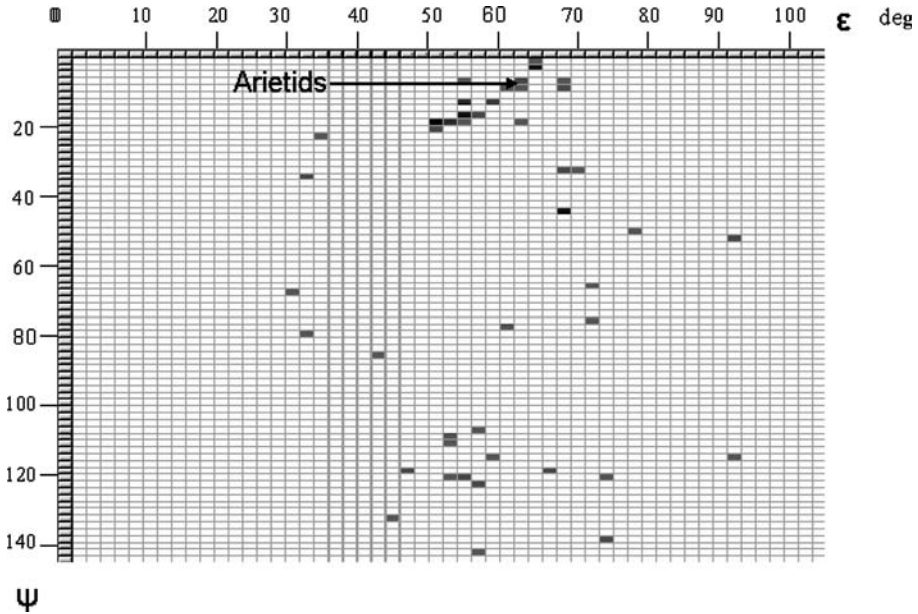


Figure 15. Microshower radiant distribution, June 16–17, 1986, $V = 36$ km/s.

the celestial sphere for December. A comparison of this figure with Figure 10 explains that the origin of the observed ring-like structures is the motion of the radar sensitivity area on the celestial sphere due to Earth's rotation.

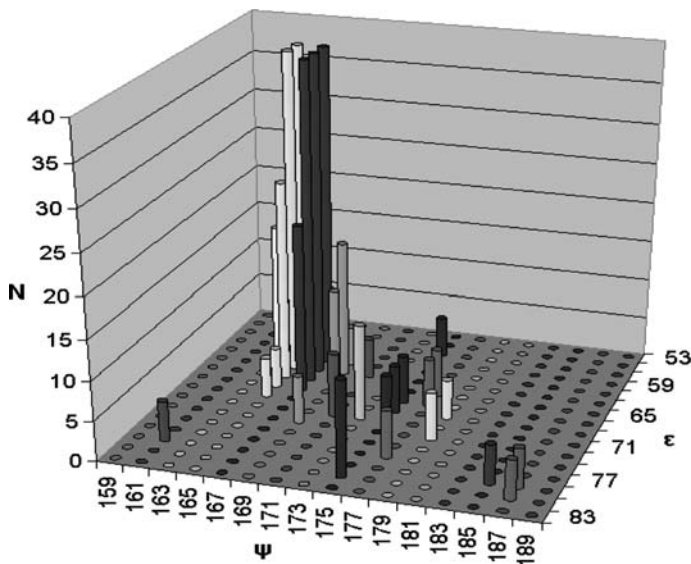


Figure 16. The microshowers acting near the Geminids in the same period.

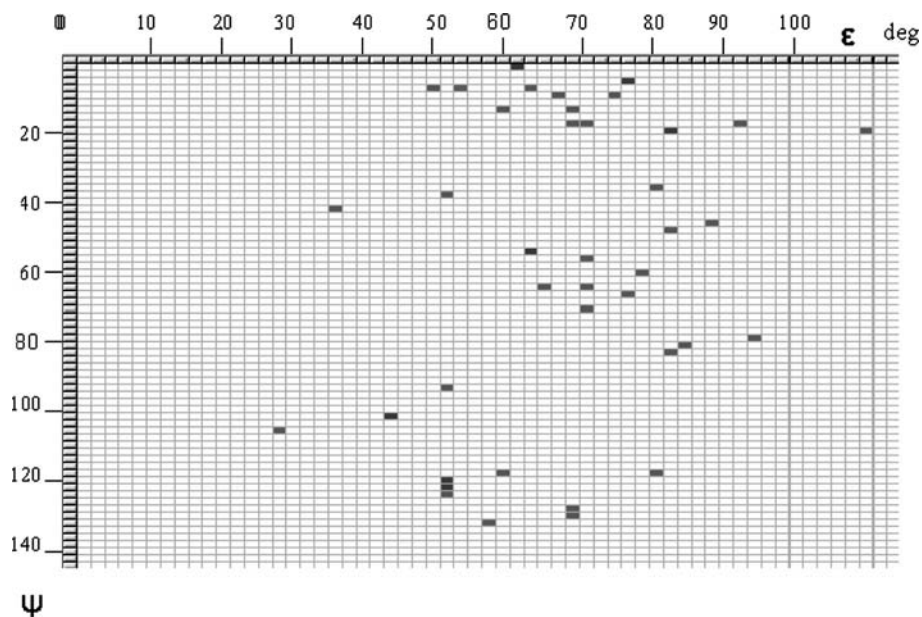


Figure 17. Microshower activity on 26–29 June in 1986.

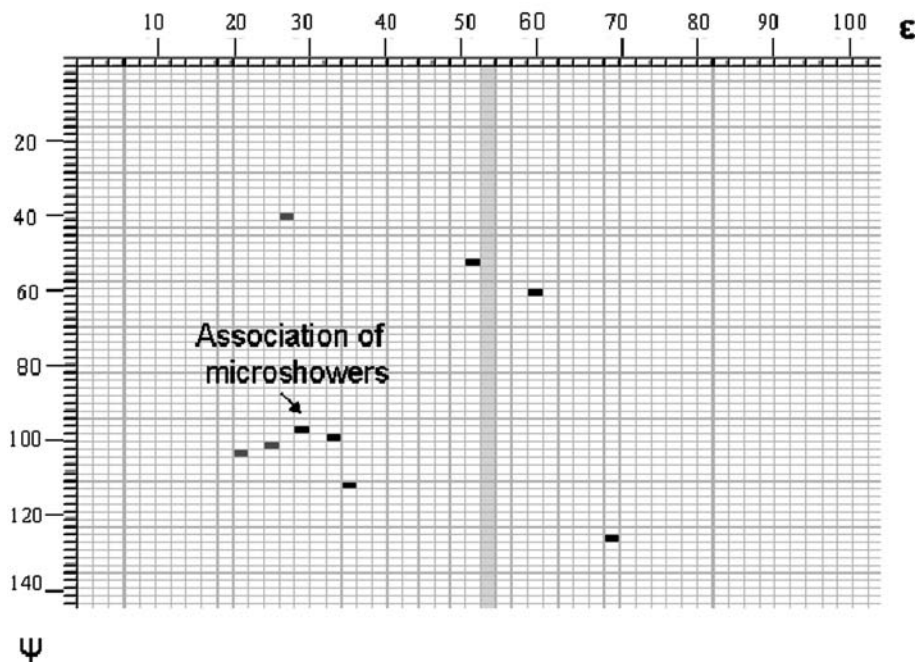


Figure 18. Association of microshowers June 25–26, 1986, $V = 54 \pm 2$ km/s.

Though a total distribution has hundreds of microshowers each microshower is really an unusual occurrence. In the following series of Figures 12–15, we can see the distributions for 2 days in June with a narrow velocity interval of 36 ± 2 km/s.

We see that most of the microshowers have associations near the area of Arietids shower, however the forms of the associations are variable.

The maximum activity is moving through an area of the Arietids radiant for more than 10 degrees. The area of Arietids radiant itself looks as long lasting as the association of microshowers. This fact essentially distinguishes Arietids from Geminids or Quadrantids. Microshowers accompanying the Geminids shower are visible in Figure 16.

The number of meteors in Figure 16 was restricted to $N = 40$ though $N_{\max}$ of Geminids is more than 300. It was made for the better view of the accompanying microshowers with the same velocity as Geminids.

Some microshowers occur in close associations with angular sizes of 10–20 degrees independent of the main showers. The activity of Arietids ends around 21 June, but by 26–29 June the association near the Arietids area radiation repeated again, thereby adding the new association (Figure 17).

In Figure 18, we can see an association acting with other velocity interval 55 ± 2 km/s on 25–26 June, 1986. A vertical line is the hyperbolic limit. Two microshowers observed on the right of the line may be hyperbolic ones. But a hyperbolic problem requires a special research.

6. Discussion

It is possible to state three possibilities concerning sources of the microshower associations that can be observed on the Earth:

- (1) Some microshowers represent the thin structure of the main region of a normal meteor shower.
- (2) Some microshowers represent concentrations of meteor particles that have been pulled out from the main body of an old large stream by the gravitational influence of planets, especially the Jovian ones. Parts of these streams scatter across the solar system and thereby sometimes intersect the orbit of the Earth.
- (3) Some microshowers are groups of simultaneously acting microshowers of meteor particles pulled from the main body of an old large shower by the gravitational influence of the Earth into relatively nearby orbits, but still have collective properties which have been kept during evolution. (Sidorov and Kalabanov et al., in this issue). It is possible to hope that such currently observable microshower associations will allow us to determine where are the native streams at present.

It is significant to know the properties of these three mechanisms to distinguish observed data and to investigate it.

7. Conclusion

We conclude that the microshowers are physically real associations of meteor particles. The microshowers characterize a significant part of the sporadic and shower components of the total meteor complex in the vicinity of the Earth.

The results of observations show the presence of the microshower associations of different structures. Its nature requires further researching.

Since the available data characterizes a correlated part of the meteor complex, we believe that most microshowers represent an intermediate stage of evolution between regular meteor streams and the uncorrelated meteor sporadic background.

This method of analysis consolidates the large experimental database that has been collected in Kazan by more than 10 years of observation into a form suitable for the direct astronomical analysis. An orbital analysis of these results (Meisel et al.) is in progress using advanced computer cluster algorithms to handle perturbations from all planets of the Sun system. This method can be applied to the analysis of data from other radars with the interferometer system.

Finally we must note that our maps of the microshower distributions, after the corrections for physical and hardware response factors can be used for prediction of meteor hazard to vehicles and people in space.

Acknowledgements

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FRAGMENTATION OF LEONIDS IN SPACE AND A MODEL OF SPATIAL DISTRIBUTION OF METEOROIDS WITHIN THE LEONID STREAM

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Abstract. The contribution presents an analysis of the Leonids 1999 HDTV Leonid MAC data. The observed grouping of the Leonids over a random level is explained by progressive fragmentation of meteoroids in space. The observed data are compared with a spatial distribution model. Possible fragmentation processes of meteoroids in space are presented and discussed.

Keywords: Meteoroids, grouping of meteors, fragmentation, radiation pressure

1. Introduction

The last return of Leonid meteor storms in 1999–2002 offered the opportunity to observe groups of meteors, possible products of fragmentation in space. The groups were observed by Japanese TV observers. Kinoshita et al. (1999) observed group of 100–150 Leonids within 2 s from Hawaii Islands in 1997. There were two other groups of Leonids observed in 2001 from Japan (Watanabe et al., 2002, 2003). The spatial size of these groups were of order 100 km (Table I).

Similar sizes of groups of meteors observed during the last several apparitions indicate that all of the possible fragmentations had to have occurred almost at the same time span before encounter with the Earth. Otherwise non-gravitational forces would spread the daughter particles over the larger areas than observed.

2. Observed Spatial Structures of Leonids 1999

We used HDTV records of Leonid storm 1999 from the ARIA aircraft (Leonid MAC) kindly provided to us by H. Yano. We found grouping of particles over the random level (Porubčan et al., 2002; Tóth et al., 2003) in the part of the HDTV record around the time of maximum activity

TABLE 1
Observed groups of Leonids (Kinoshita et. al., 1999; Watanabe et al., 2002; 2003)

Time (UT)	Duration (s)	Number	Spatial size	
			$\parallel$ (km)	$\perp$ (km)
13:31, November 17, 1997	2	100–150	100	50
17:56, November 18, 2001	2	> 15	~100	~100
18:29, November 18, 2001	2	38	150–200	100

Duration – the apparition of the whole group in seconds, Number – group members, Spatial size – size of the group along the stream $\parallel$ and perpendicular to the stream $\perp$.

(November 18, 1:58:20–2:01:20 UT). We present here an analysis of detail spatial distribution of meteors within the groups which occurred in this part of the record. Since observations of only one station are available, we have to assume the average height of Leonids for calculations of distances. We assumed the height of 107 km for the maximum brightness of Leonids 1999, which is almost constant for the mass range of observed meteors (Koten and Borovička, 2001; Brown et al., 2002). We used astrometric data from METREC – automatic meteor detection software (Molau, 1999). We obtained 103 meteors in close groups with the size less than 200 km, which is similar in size to previously observed groups of Leonids (Table I). The magnitude range was from -2 to $+4$, with a possible error for a particular meteor up to three magnitude (Campbell-Brown and Koschny, 2004). But standard deviation of METREC magnitudes was about $\pm 1^m$. The average difference (O-C) of the astrometric position of reference stars was 1.4 arcmin. We calculated the distance of each meteor from the station and distances between successive meteors in groups. The uncertainty of the distances of meteors is about 5–10%.

We observed three types of meteor structures of Leonids 1999. The first one is very close pairs on the spatial scale 10^1 km. The second type is groups (2–5 members) with typical distances less than 200 km. The third type of structures are “free” groups (5–12 members) with the typical distances about 500 km. The METREC software was not able to detect all meteors, especially faint one. At least 18% of all meteors belong to the first two types of groups. We detected about 2/3 of them in pairs and just 1/3 in groups with more than 2 members. This could be a selection effect of the observation, where fainter meteors were not detected due to the observation near the horizon and lower efficiency of METREC software for fainter meteors. We calculated the distances between successive meteors in the first two types of groups for two selected directions: along the stream and perpendicular to the stream. The obtained distribution of these distances is plotted in Figure 1. Distance distribution exhibits maximum for ≈ 50 km in both directions.

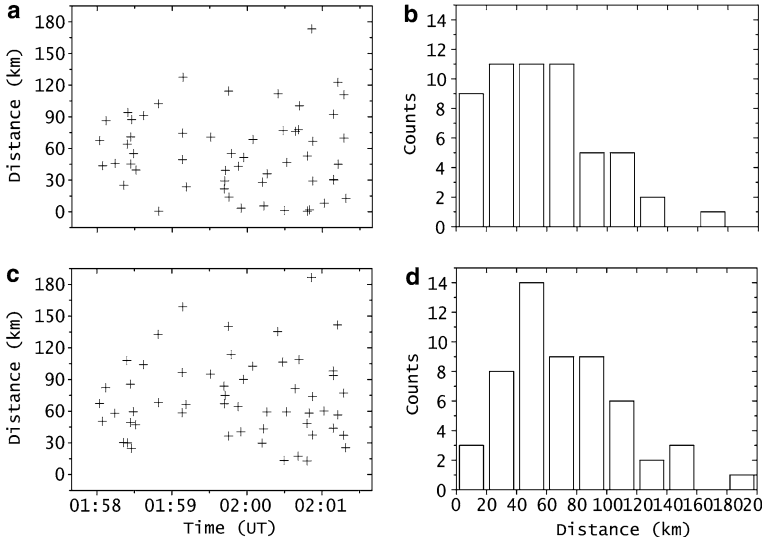


Figure 1. Time distribution of the distances between successive meteors (a, c) and range distribution (b, d) in the first two types of groups of Leonids 1999. The distributions along the stream (perpendicular to the stream) are shown in plots a and b (c and d).

Naturally, there are some random meteors among meteors we classified as close pairs or groups. But, the portion of random meteors is less than $1/3$ of all meteors in close pairs or groups.

We also observed “free” groups of meteors producing jumps in meteor rates (Figure 2). The rate of Leonids on interval more than 30 s is almost constant (Figure 2a), but the counts of meteors in intervals less than 10 s are about 2 or 3 times over the average level (Figure 2b, c, and d). These structures could not be products of the inhomogeneous ejection from the parent comet 100 years before, because original structures have to be erased due to the non-gravitational and gravitational forces as it is clear from our orbital evolution modeling after the fragmentation mentioned below. The fragmentation is probably responsible for such jumps in the rate of meteors on few seconds time scale.

3. Model of the Fragmentation

The average brightness of meteors in the groups is about $+2^m \pm 1^m$. The corresponding absolute magnitude is $0^m \pm 1^m$ and the corresponding mass is $\approx 10^{-2}$ g (Ceplecha and McCrosky, 1976). The diameter for a spherical particle is 3 mm if the assumed density for Leonids is 0.7 g cm^{-3} (Spurný et al., 2000). Then the β_1 parameter for such particle is ≈ 0.0005 (β is the dimensionless efficiency factor describing effect of radiation pressure on

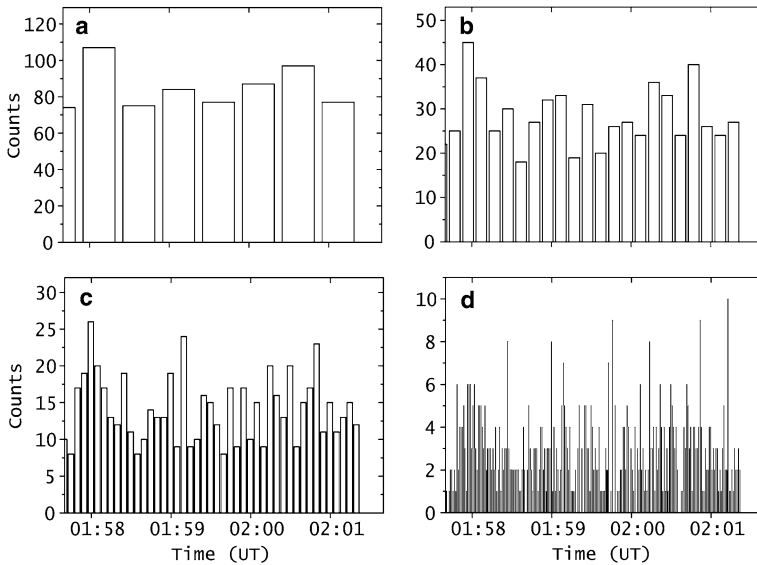


Figure 2. The counts of Leonids near the peak of 1999 storm from HDTV camera in 30 s intervals (a), 10 s intervals (b), 5 s intervals (c) and 1 s intervals (d).

spherical dust particle). The faintest observed meteors yield $\beta_2 \approx 0.001$. There is a high abundance of faint meteors in the observations. For this reason we selected $\beta_2 = 0.001$ as a typical value of post-fragmentation meteoroids. We used $Q'_1 \approx 1$, where Q'_1 is the radial component of the particle's radiation pressure efficiency (Klačka, 2004).

We modeled the orbital evolution of a typical pair of meteoroids with β_1 and β_2 . We assumed zero ejection velocity vector during the fragmentation and the spread of the daughter's particles characterized by β_1 and β_2 are due to the gravitational and solar pressure forces. The modeling indicates that the fragmentation occurred about 2.1 days before entry into the Earth's atmosphere. It is about 3.5 days after the perihelion passage. We do not know precise β parameter of each daughter particle after the fragmentation, which depends on its mass, dimension, density or parameter Q'_1 . However, if we use realistic range of the β values (0.0001–0.004) for meteoroids we observed, we obtain the time interval 0.8–4.7 days of possible fragmentation in space before entry to the atmosphere.

Similarly, if we model the evolution of the third type of Leonid group (“free” groups) with the typical distances about 500 km with the same type of meteoroid pair, the fragmentation should occurred about 2.4–14.8 days before the entry to the atmosphere. This is a recent fragmentation in space. This indicates that the fragmentation occurred at least near perihelion and we can observe grouping of meteors only after recent fragmentation events.

4. Discussion

Our previous paper about possible fragmentation of Leonids 1999 (Tóth et al., 2003) found grouping of meteors over the random level. There was enhancement of successive meteors on time scale 0.033 s. But the spatial distribution reveals only a small number of such very close meteors which could correspond to this time scale. The enhancement on 0.033 s time scale is probably due to the presence of “free” groups (third type of structures introduced in Section 2). Their members raise the number of meteors to two or three times over the average level (Figure 2). This could lead to a higher concentration of meteors with the non-random distribution of meteors.

It is interesting that the observation from the same airplane during Leonid MAC 1999 near the activity maximum by other authors (Gural and Jenniskens, 2000) did not show the presence of the grouping of meteors over the random level. However, there are some differences in observation and analysis, too. The observation by HDTV camera were performed on the North side of the plane, as opposed to the AL50R camera, which observed near the South horizon (Gural and Jenniskens, 2000). Also the size of the field of view and limiting magnitude are different, which resulted in about twice the meteor rate (Tóth et al., 2003). Naturally, if fragmentation is responsible for the grouping of meteors, one would expect a higher presence of faint meteors in groups as products of the fragmentation. But probably the crucial difference is the analysis of the data. We found the grouping of meteors just in the particular time interval 1:58:02–2:01:22 UT (November 18, 1999), but not in others from 1:51–1:58 UT. Gural and Jenniskens (2000) analyzed the whole data set from 1:50:00 to 2:06:41 UT, where presence of the grouping were probably statistically smoothed.

5. Conclusion

We could not observe the actual fragmentation of meteoroids in space, but we observed the grouping of meteors both in time (Tóth et al., 2003) and in space (this paper). We suggest that a progressive fragmentation of meteoroids in space could explain the observed grouping of meteors. The model of the orbital evolution indicates a recent fragmentation of meteoroids about a few days before collision with the Earth, which is around the perihelion passage. Also it suggests the fragmentation due to thermal heating near the perihelion. About 10% of the whole population of Leonids, observed in the particular time interval 1:58:02–2:01:22 UT (November 18, 1999), were possible fragments of a recent fragmentation in space.

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MASS FLUX OF ASTEROIDAL ORIGIN METEORIODS ON PERIODIC COMET NUCLEI

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Abstract. We examine the potential contamination of cometary nuclei through impacts from asteroidal origin meteoroids. The paper uses a simple model and has the goal of determining whether asteroidal contamination is potentially significant. We assume a meteoroid power law mass distribution with index values in the range from $s=1.83$ to $s=2.09$. We used maximum and minimum models which we believe will bracket the true meteoroid mass distribution. We identify those comets which are expected to be most significantly contaminated, and find values of up to 3.6 kg of asteroidal meteoroid impact per square meter of the cometary surface per orbital revolution. This is less than the expected mass loss per perihelion passage for most comets. Therefore any remnant effects of the contamination will depend on the penetration depth of the meteoroids in the cometary nucleus, and possibly on the distribution of active and inactive areas on cometary nuclei. We present a simple model which suggests that even small meteoroids will embed relatively deeply into a cometary nucleus.

Keywords: Asteroid, cometary nuclei, contamination, meteoroid

1. Introduction

In this paper we model the interaction of asteroidal origin meteoroids with cometary nuclei. The goal was to determine if cometary material suffers significant contamination by collisions with asteroidal origin meteoroids. If the contamination is significant, then when we sample cometary material, either through space missions or through studying meteoroids of cometary origin, the material will be a mixture of cometary and asteroidal material. While the topic of meteoroid collisions with cometary nuclei has been considered by several authors (e.g. Sulc et al., 1994; Gronkowski, 2004), to our knowledge this is the first study of the meteoroids mass influx to different cometary nuclei. The model which we will employ is a very simple one, and our goal was to determine if development of a more sophisticated model is warranted. We will use two meteoroid mass distributions to bracket the true mass distribution.

2. Computational Model

For the mass distribution of asteroidal origin meteoroids we assumed that the number of meteoroids, dN , with masses between m and $m + dm$ is given by

$$dN = Cm^{-s} dm \quad (1)$$

If s is less than 2 the mass distribution is dominated by larger meteoroids and if s is greater than 2 the mass distribution will be dominated by smaller meteoroids. We adopted two sets of model parameters, with the goal being that the actual meteoroid mass distribution would fall somewhere between these extreme values. Dohnanyi (1969) showed that if a system of colliding asteroidal meteoroids reaches a steady state collisional environment then $s = 1.83$, a result supported by Williams and Wetherill (1994). While collisional equilibrium is certainly not true for larger asteroids, it may well be appropriate to the smaller meteoroids. Observational evidence suggests that the actual mass distribution index s is somewhat larger than the Dohnanyi value, with sporadic meteors usually following mass distributions with s of the order of 2.0. As our maximum model we selected $s = 2.09$ (Hughes and Harris, 1994) which was based on an extrapolation from the observed mass distribution of the smaller asteroids. The actual mass distribution is almost certainly not strictly constant in s value (Campo Bagatin et al., 1994; Ceplecha et al., 1998; Jedicke et al., 2002; Bottke et al., 2005), but we feel confident that our maximum and minimum models will span the true mass flux value.

In order to set values for C we followed the approach of (Hughes and Harris, 1994) and assumed that the observed asteroid size distribution is complete (for main belt asteroids) down to at least 130 km. We used the observed population of objects of this size to determine C . The observed asteroid size distribution is probably essentially complete to somewhat smaller asteroids Jedicke et al. (2002). One potential weakness of the approach used here is if the mass distribution of the larger asteroids do not accurately reflect the collisionally derived population because they are primordial relics (Bottke et al., 2005). Recently Yoshida and Nakamura (2004) have suggested that the mass distribution is slightly different in the inner and outer regions of the main belt.

The total mass, M_T , of the asteroidal origin meteoroid cloud can be determined by multiplying Equation (1) by the mass m , and then integrating. In Equation (2) m_L and m_S represent the assumed largest and smallest mass values.

$$M_T = \frac{C}{2-s} [m_L^{2-s} - m_S^{2-s}] \quad (2)$$

We selected, probably conservatively, 10^{-6} kg for the smallest mass. Very small masses will be removed from the asteroidal cloud by radiation pressure and Poynting-Robertson drag as well as collisional losses. Meteoroid masses at least this small are present in meteor showers with asteroidal parents such as the Geminids (Simek and McIntosh, 1989). The work of (Ceplecha, 1987) suggests that there are significant contributions of asteroid origin meteoroids at least down to the mass limit of television meteor studies (10^{-5} kg).

For the largest mass, we assumed that the largest meteoroids were 1 m in radius, which if spherical and of density 3500 kg m^{-3} , corresponds to a mass of about 15000 kg. While one could use a larger value, since clearly much larger objects exist in the asteroid belt, generally objects larger than about 1 m are not considered meteoroids, and would not correspond to the contamination effects studied in this paper. In meteoroid streams with asteroidal parents, such as the Geminid shower, there is evidence that meteors at least near this size exist.

We show the values of C and the total mass of asteroidal origin meteoroids for the maximum and the minimum models in Table I. A different value for the largest mass would only slightly change the maximum model total mass, while it would significantly alter the minimum model.

For asteroidal meteoroid orbital parameters we assumed that the meteoroids follow the orbital distribution of main belt asteroids. We used all main belt asteroids with absolute magnitude brighter than +11 (assuming that the orbital distribution is essentially complete for these relatively bright asteroids) to define an orbital probability distribution function. Since this population is complete, it is not necessary to apply de-bias techniques (Jedicke et al., 2002). We used a Monte Carlo approach to simulate 5000 asteroid positions based on the orbital elements of asteroids brighter than absolute magnitude +11. We used the positions of these simulated asteroids to define a probability distribution $p(R, R_z)$ where R is the heliocentric distance and R_z is the distance above or below the ecliptic plane. Our probability value approached zero, and was set exactly to 0, at R_z values of magnitude more than 1.6 au, and for R values less than 1.4 au or more than 5.1 au. The integrated value of the function $p(R, R_z)$ is called the probability volume, V_T .

TABLE I

Model parameters used for the minimum and maximum models for asteroidal origin meteoroids in the main asteroid belt

Model	s	$C(\text{SI units})$	Total Mass (kg)
maximum	2.09	2.16×10^{22}	7.3×10^{23}
minimum	1.83	2.39×10^{17}	7.0×10^{18}

Orbital parameters for 116 short period comets were taken from the Minor Planet Centre Catalog (Marsden and Williams, 1995). In our numerical model each comet orbit was divided into 10,000 equal time intervals. To find the probability volume intercepted by a comet in each interval we multiply the probability of finding asteroidal origin meteoroids in that interval, $p(R, R_z)$, by the assumed cross sectional area of the comet, A , and by the linear distance travelled, $(\Delta\xi)$, by the comet in the time interval. To get this as a mass intercepted we need only multiply by the total mass of the meteoroid cloud, M_T , and divided by the integrated probability volume of the cloud, V_T . This is represented by the following equation.

$$\Delta m = \frac{p(R, R_z) A \Delta \xi}{V_T} M_T \quad (3)$$

3. Results

Since the actual dimensions of most comets are not well known, we computed the mass influx in terms of the meteoroid mass intercepted per orbit per square meter of the cometary surface. The comets which have the largest influxes of asteroidal material per orbital revolution are given in Table II. It can be shown that according to the maximum model a number of comets intercept more than one kilogram of asteroidal debris per square meter per orbit. The masses according to the minimum model are generally in the tens of microgram level, and are negligible.

If we use the maximum model, then we obtain a mean (over all the comets studied) mass influx of 3.3×10^8 kg per orbital period on a 5 km radius cometary nucleus. This mean flux would only correspond to less than 1.2 mm around the surface of a 5 km radius comet if a mean mass density of 1000 kg/m^3 is assumed. Therefore if the contamination is restricted to the surface of the nucleus this contamination will be removed each orbit. However, it is likely that some of the asteroidal dust will penetrate well below the surface so contamination is still possible. In the next paragraph we develop a very simple model to evaluate this effect.

We will assume that the impacting meteoroid is spherical and has mass m , radius r , density ρ and mass relative of the comet v . In the following derivation we assume that a portion α of the incident meteoroid's kinetic energy is used to compress the cometary material (other energy goes into other deformations and heating). More sophisticated penetration models are possible. Let d represent the penetration depth of the meteoroid in the comet. If

TABLE II

Model results for the 30 comets which have the largest amount of asteroidal meteoroid contamination. The mass flux (in kg) of asteroidal debris intersected per orbital passage of the comet per square meter of cometary surface is given. The middle column gives the results when the minimum model of Table I is used and the right column gives similar results using the maximum model

Comet	Incident Mass Flux (Minimum) (kg per m ² per orbit)	Incident Mass Flux (Minimum) (kg per m ² per orbit)
Kojima	3.5×10^{-5}	3.6
Russell-4	3.0×10^{-5}	3.1
Bus	2.9×10^{-5}	3.0
Shajn-Schaldach	2.5×10^{-5}	2.7
Chernykh	2.4×10^{-5}	2.5
Schwassmann-Wachmann-2	2.4×10^{-5}	2.4
Spitaler	2.4×10^{-5}	2.4
Wild-4	2.3×10^{-5}	2.4
Slaughter-Bernham	2.2×10^{-5}	2.3
Gehrels-2	2.2×10^{-5}	2.3
Van-Biesbroeck	2.2×10^{-5}	2.3
Russell-2	2.2×10^{-5}	2.3
Gunn	2.1×10^{-5}	2.2
Giclas	2.1×10^{-5}	2.2
duToit-Neujmin-Delporte	2.1×10^{-5}	2.2
Neujmin-3	2.0×10^{-5}	2.0
Whipple	1.9×10^{-5}	2.0
Gehrels-3	1.9×10^{-5}	2.0
Kearns-Kwee	1.9×10^{-5}	2.0
Hartley-3	1.9×10^{-5}	1.9
Oterma	1.8×10^{-5}	1.9
Singer-Brewster	1.8×10^{-5}	1.9
Wild-2	1.8×10^{-5}	1.8
Reinmuth-2	1.8×10^{-5}	1.8
Gehrels-1	1.8×10^{-5}	1.8
Howell	1.7×10^{-5}	1.7
Maury	1.6×10^{-5}	1.7
du-Toit-Hartley	1.6×10^{-5}	1.7
Brooks-2	1.6×10^{-5}	1.6
Wilson-Harrington	1.5×10^{-5}	1.6

S is the mean compressive strength (units of force per area) of the cometary material, then the work which must be done for compression is given by the product of the force (which is S times the cross sectional area of the

meteoroid) times the penetration depth d . We obtain the relationship given in Equation (4) for the assumption of spherical meteoroids.

$$\alpha \frac{1}{2} mv^2 = dS\pi r^2 \quad (4)$$

Since we have assumed spherical meteoroids, m and r are related by the following.

$$m = \frac{4}{3} \pi r^3 \rho \quad (5)$$

Combining Equations (4) and (5) we obtain the following relationship for the penetration depth d .

$$d = \frac{2\alpha\rho v^2 r}{3S} \quad (6)$$

We can combine Equations (6) and (5) to express the depth of penetration, d , as a function of the mass, m , and density, ρ , of the incident meteoroid.

$$d = \alpha \frac{v^2}{2S} \left(\frac{16\rho^2 m}{9\pi} \right)^{1/3} \quad (7)$$

This simple model (if one adopts $\alpha=0.05$) suggests that a 1×10^{-5} kg meteoroid with a relative velocity of 5 km/s would impact to a depth of 0.022 m if a very strong cometary nucleus with S of 5×10^7 N/m² is assumed, or more than 200 m if a loosely structured rubble pile with S of 5×10^3 N/m² is assumed. It should be pointed out that more sophisticated models for interaction of meteoroids with porous cometary nuclei exist (Toshihiko, 1999), although that study is more applicable to much larger meteoroids than those under investigation here. The experimental studies of impacts of small objects into icy bodies should also be noted (e.g. Arakawa et al., 2000; Koschny et al., 2001).

4. Discussion

The study showed great variability of asteroidal meteoroid mass influx for different comets. If one uses the maximum model, and assumes a spherical comet of radius 5 km, then almost 10^9 kg of asteroidal meteoroids will be impacted per orbit in the case of the comets with most contamination in Table II. However, even this value is much less than the mass loss per orbit due to sublimation. The contamination will only be significant if the meteoroids penetrate deep into the cometary nucleus, or if significant regions of the crust are dormant from mass loss for significant periods. A simple

TABLE III

Model results for comets which are parents of meteor showers, or for which space missions are underway or have been proposed. The mass flux (in kg) of asteroidal debris intersected per orbital passage of the comet per square meter of cometary surface is given. The middle column gives the results when the minimum model of Table I is used and the right column gives similar results using the maximum model

Comet	Incident Mass Flux (Minimum) (kg per m ² per orbit)	Incident Mass Flux (Minimum) (kg per m ² per orbit)
Biela	7.9×10^{-6}	0.82
Borrelly	1.9×10^{-7}	0.02
Churyumov-Gerasimenko	1.1×10^{-5}	1.09
d'Arrest	1.8×10^{-6}	0.18
Encke	9.4×10^{-6}	0.98
Giacobini-Zinner	2.7×10^{-7}	0.03
Halley	4.9×10^{-6}	0.51
Schwassmann-Wachmann-3	7.5×10^{-6}	0.79
Swift-Tuttle		
Tempel-Tuttle	1.4×10^{-6}	0.14
Tempel-1	9.9×10^{-6}	1.03
Tuttle	7.1×10^{-8}	0.007
Wild-2	1.8×10^{-5}	1.82

penetration model suggests that even small meteoroids may penetrate deep into a porous cometary nucleus, resulting in deep meteoroid contamination. One of the goals for this research was to investigate how seriously cometary nuclei which are studied by space missions and those which serve as parents for meteor showers are contaminated. We show in Table III the results for the relevant comets.

The comets responsible for many of the significant meteor showers have relatively small mass influxes according to our model. For example, essentially zero for the Perseids (Swift-Tuttle), very low for the Ursids (Tuttle) and Draconids (Giacobini-Zinner), moderately low for the Orionids (Halley), η -Aquarids (Halley), and Leonids (Tempel-Tuttle), and relatively high for the Taurids (Encke). Three comets with space mission investigations (Wild 2 for Stardust, Tempel 1 for Deep Impact and Churyumov-Gerasimenko for Rosetta) all have moderate levels of asteroidal meteoroid mass influx. The meteoroid mass flux for Borrelly (Deep Space I) is relatively low.

In this paragraph we will discuss limitations in the model employed. The most significant weakness is the simple mass distribution models employed, which left a very large span between the minimum and the maximum models. A more precise treatment will need to allow for changes in mass distribution

slope according to mass, and possibly according to orbital characteristics. The orbital characteristics of large asteroids were used to model the orbital characteristics of asteroidal meteoroids – there are certainly some differences due to collisional and radiative effects. Only main belt asteroid meteoroids were considered and Trojan asteroids may affect some comets. The research reported here only attempted to account for a mass influx to the cometary nucleus; no account was taken of ejection of material following impact. The penetration depth model used is a simple one. Also, it should be kept in mind that the goal of this work was to estimate the mass influx from *asteroidal origin* meteoroids. The total meteoroid influx on cometary nuclei, including meteoroids of cometary origin, would be much greater.

The goal of this preliminary paper was to evaluate the potential significance of cometary contamination due to asteroidal meteoroid impact. The results suggest that the effects may range from totally insignificant to modest. If large areas of the comet remain inactive for extended periods, or if the structure of the cometary nucleus results in deep penetration, contamination may be a significant effect. The results of this research point to the need for a more detailed investigation of the interaction between asteroidal meteoroids and cometary nuclei.

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INTERSTELLAR DUST IN THE SOLAR SYSTEM

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Abstract. Dust is an important component of galactic structure and the cyclic processing of particulate matter leads to stellar and planetary formation. Though astronomical methods using analysis of dust-penetrating starlight can provide some limited information about the dust, the prospect of its *in-situ* sampling within the Solar System by spacecraft and its remote sensing by ground-based techniques open up a new field in galactic exploration.

Keywords: Interstellar-dust, meteor, meteoroid, solar-system

1. Introduction

Sampling Interstellar Dust (ISD) within the bounds of the solar system can be accomplished via several techniques – particularly *in-situ* by spacecraft, meteorites, atmospheric collections and by atmospheric impact producing meteors – yielding light emission or plasma. Evidence of the interstellar nature of such particulates requires knowledge of their dynamical, chemical or isotopic characteristics. Sampling of ISD in the solar neighbourhood will enhance our understanding of the galactic environment by fixing the solid component mass ratio and permitting the identification of dust sources. Before discussing the detection and sampling of ISD it is useful to briefly summarise some of the factors that govern dust processes on the galactic scale.

2. The Galactic Dust Environment

The re-cycling of solid material from its production in stars and subsequent evolution via molecular clouds into stellar and planetary systems is a fundamental galactic process and access to the solid agglomerations of heavy elements provides us with opportunity to gain significantly in our understanding of the controlling processes in the Galaxy. Chemical sampling of

grains is an important goal and some dust may retain an isotopic record of nucleosynthesis in their source stars. Discrete sources of the dust component are thought to be condensation within the expanding atmospheres of AGB (asymptotic giant branch), RGB (Red Giant Branch) carbon rich stars and Wolf-Rayet stars; protoplanetary dust discs in evolving stellar systems; and Supernova. Local sources of dust are expected in star forming regions such as the Scorpius-Centarus Association while the specific geometrical configurations of dust debris discs may govern particulate ejection in favourable (sunward) directions. Several examples of protoplanetary discs have been imaged in the Infra-Red (0.8–2.5 microns) by the HST Near infrared camera multi-object spectrometer.

The characteristics of UV, visible and IR spectra observed in astronomically long sight-lines to stars have enabled reliable models to be constructed of the constituents of interstellar dust as composed of various combinations of amorphous silicates, graphite, and PAH (polycyclic aromatic hydrocarbons) molecules, while modelling has been carried out of the processing of dust in varied galactic environments (see Frisch, 2000 and references therein).

There has been work modelling both dust evolution (Liu, 2004) and ejection (Krivov et al., 2003) in proto-planetary discs and on interstellar dynamics (Baggaley and Nuslusan, 2002; Murray et al., 2004).

The large scale dust inter-connections within the Galaxy might provide a possible mechanism for the transport of complex organic molecules (as pre-biotic building-blocks) or even micro-organisms over galactic distances. Planetary systems may not be biologically isolated: for example over its history the solar system has passed through dark dust cloud complexes and giant molecular clouds. Oscillations through the galactic plane with a period of ~60 My and encounters with nearby stars may eject solid material into the solar system. In a developed stellar system large body impacts onto a bio-rich planet may cause the ejection of boulders enriched by microorganisms with subsequent erosion and fragmentation and ejection of component grains as β meteoroids. Embedded in the mantle of such grains (and so protected against irradiation from stellar UV and galactic cosmic rays) such biotic material may survive galactic transport (Melosh, 2003; Napier, 2004).

3. Flow into the Solar System

Only partial penetration of ISD into the inner solar system can occur with the heliopause at ~80 A.U. acting as filter. Small grains are coupled closely to the flow of H and He gas of the Local Interstellar Cloud (LIC), electrostatic charging (Horanyi, 1996) of grains occurs by ambient plasma and solar UV so that Lorenz forces act in the presence of the magnetic field carried by the radially expanding solar wind. In addition, absorption of solar energy

produces a radiation pressure that opposes gravity: the ratio of the radiation force to gravity force, β , is independent of solar distance and depends on the grain mass and optical properties of the grain material. As illustration, for radii of $0.5 \mu\text{m}$ $\beta \sim 1.6$ for silicate grains. In consequence, grains have non-Keplerian orbits and powerful mass-dependent filtering is imposed which (because the magnetic field depends on the solar state) is solar cycle dependent (Landgraf, 2000). For grain sizes $\gtrsim 2 \mu\text{m}$ forces are gravity dominated, whereas for masses $\lesssim 10^{-17} \text{ kg}$ (sizes $\lesssim 0.1 \mu\text{m}$) complete shielding occurs.

Directional filtering of ISD will occur during their journey in the galaxy: close coupling to the local gas flow and the interstellar magnetic field (Grün and Landgraf, 2000) will exist with scale-lengths ranging from $\sim 1 \text{ pc}$ for dust $\sim 1 \mu\text{m}$ to $\sim 10^3 \text{ pc}$ for $\sim 50 \mu\text{m}$: only for large grains will streaming directions with respect to the local standard of rest directly reflect source locations.

There are (at least) four populations of dust which can acquire excess energy and so yield unbound orbits within the solar system: discrimination is required to recognise that component that is truly of external origin. Dust ejected from a comet having a near-parabolic orbit (e.g. comet P/Halley has an eccentricity ~ 0.96) and leaving the nucleus parallel to the velocity vector can achieve speeds in excess of the solar escape speed. A population of meteoroids having speeds in excess of the parabolic limit and in the ecliptic plane are the β particles generated close to the sun by collisional interactions. Dust streams have been detected by near-Jupiter probes which result from acceleration by electric fields to high speed from origins in the Jovian system. Rare close encounters of a closed orbit particle with a major planet can result in an increase in orbital energy sufficient to yield a hyperbolic orbit.

A deposit of primordial ISD dust might be expected to have accumulated on some exposed surfaces in the outer solar system (avoiding contamination by IPD) – on Trans-Neptunian Objects and outer planetary satellites.

4. Spacecraft Detection

4.1. IMPACTS

In-situ sampling of ISD has been possible via the Pioneer 8 and 9, Hiten, Galileo, Ulysses, Cassini and Helios craft and the current Stardust mission. A variety of onboard instruments measured flux, speed and low-precision directions. Detectors developed by the Heidelberg Dust Group (Grün et al., 1992) of $\sim 0.3 \text{ m}^2$ collecting area sense a dust particle's induced electrostatic charge via spaced grids to yield velocity and mass from ions produced as a result of impacts with a rubidium target; additionally CIDA (Cometary and Interstellar Dust Analyser) – a time-of-flight mass spectrometer with $\sim 1\%$

mass resolution. Dust detection instruments require extensive laboratory calibration and the development of techniques to accelerate grains to cosmic speeds (e.g. comet encounter speeds of 63 km s^{-1} for the Giotto-Halley pass in March 14, 1986 to 6 km s^{-1} for the Stardust-Wild2 encounter January 2, 2004).

Any inner solar system sampling of ISD must have the ability to resolve the target galactic dust in the presence of the overwhelming solar-bound interplanetary material (IPD) (Brownlee, 1985) originating in comets and asteroids. While the flux of ISD is relatively uniform within the heliosphere, the IPD form a cloud symmetrical about the ecliptic plane with spatial density latitudinal width $\sim 30^\circ$ and radial decrease with solar distance as $\sim r^{-1.3}$.

The Cassini and Helios probes measured the near-ecliptic ISD flux (see Altobelli, 2003) but especially ideal was the trajectory of Ulysses which used Jupiter gravity swing-by to achieve an orbit at 89° ecliptic inclination with aphelion distance of $\sim 5 \text{ A.U.}$ Because of the ability to reach large ecliptic latitudes and large solar distances the proportion of ISD to IPD improved greatly and the ability to discriminate prograde from retrograde particles isolated a clear interstellar component.

4.2. SAMPLE-RETURN

The Stardust probe was launched February 7, 1999 to secure ISD collection and Earth return. The major feature of the mission is to capture both cometary grains from the coma of comet Wild2 as well as ISD by decelerating grains from their craft-comet impact speed (6 km s^{-1} for comet and $\sim 25 \text{ km s}^{-1}$ for ISD for particular collection orbit phase) and so to secure grains intact and undamaged by the procedure. Two periods of exposure to ISD, avoiding exposure to β meteoroids were planned – when the vehicle tracked parallel to and downstream to (to reduce the impact speed to a minimum) the ISD inflow: 110 days on Orbit 1 (after gravity assist via Venus and Earth the Stardust mission having three solar orbits) of the mission Feb–May 2000; and on Orbit 2 136 days Aug–Dec 2002. These periods were prior to comet flyby on Jan 2, 2004. During the mission shields were in place to protect the main spacecraft during encounter with the cometary dust coma. After comet flyby the dust capture aerogel was stowed into the sample return capsule to await Earth re-entry Jan 15, 2006 (Kissel et al., 2004).

5. The Earth as a Detector of ISD

ISD and Pre-solar grains – recognisable by the presence of elements with non-solar isotopic ratios have been studied in meteorites (Mostefaoui et al.,

1998; Hoppe and Zinner, 2000) and stratospheric aircraft collections (Messenger et al., 2003). Laboratory studies of such material over the last few years has opened up an important new tool in galactic dust astronomy. Isotopic and structural studies making use of new developments in ion probes (Nittler, 2003) have enabled specific minerals (e.g. silicates – olivines, pyroxenes, Diamonds; Graphite; Silicon Carbide; Spinel (MgAl_2O_4); and Carborundum (Al_2O_3)) to be associated with specific sources – either stellar ejection or supernovae (e.g. Nittler et al., 1995).

As a solid grain decelerates in the Earth's atmosphere enough heating may occur to generate sufficient light or ionisation to permit detection as a meteor. The lower limit for unimpeded access to the solar system of $\sim 2 \mu\text{m}$ for spacecraft data (also the approximate upper limit set by statistical sampling but also detector saturation or indeed damage) is below the limit of $\sim 10 \mu\text{m}$ (dependent on speed) for detection as a meteor. This limit arises because during the interaction of a meteoroid of size less than this value the radiation rate from the surface area of the acquired kinetic energy is greater than the energy that goes into body heating and incomplete ablation occurs (Rietmeijer, 2002).

The effective collecting area for a ground-based single sensor (camera or radar) when using the atmosphere as a detector is of order 10^3 km^2 (depending on the technique used). Interestingly, this much larger area nearly compensates for the larger flux of smaller grains available for spacecraft detection because of the mass distribution characteristics, so that the actual detection rates of ISD by the quite different techniques are of the same order.

6. Meteor Orbits

Influxing meteoroids larger than the micrometeoroid limit dissipate kinetic energy via atmospheric interaction to yield columns of excited species – that can be sensed by visual, photographic, image intensifier, CCD – and also ionisation that can be sensed by radar. By remote sampling such a column at separated points along the trail the atmospheric trajectory of the ablating meteoroid in the atmosphere can be delineated and from that the path in space. Since the measurement is made on a moving platform and performed in a gravity field, several effects need accommodating: the rotation of the Earth – the motion of the station varies with latitude; deceleration in the atmosphere – the pre-entry needs fixing; the modification of the space motion in the gravitational field of the Earth; and the orbital motion of the Earth. Employing these corrections provides the path outside the sphere of influence of the Earth and so fixes the heliocentric orbit. It is in the dynamical measurements for which trajectory-sensing meteor surveys are especially

valuable. Several stages in the development of advancing techniques can be identified in the provision of evidence by meteors for ISD.

6.1. VISUAL METEORS WITHOUT INDIVIDUAL ORBITS

The solar parabolic speed at the Earth varies from 41.4 to 42.8 km s⁻¹ depending on the Earth's orbital position and therefore date. The atmospheric speed depends on the Earth's orbital speed, the particle's energy increase in the Earth's gravity field and the relatively minor effect of the observer's latitude-dependent motion due to the Earth's rotation. The atmospheric speed to an observer depends on the elongation of the meteor's radiant from the Earth's Apex direction and varies from 72.8 km s⁻¹ for zero elongation to 16.4 km s⁻¹ for 180°. In the 1920s and 30s campaigns provided catalogues of estimates of individual topocentric speeds and radiants in attempts to establish whether a significant proportion of speeds so determined indicated solar hyperbolic speeds. Using a single station a measurement of angular speed and visible track elevation together with an assumed mean height will provide approximate range and hence linear speed; an estimate of the radiant provides the elongation from the Earth's Apex. Catalogues compiled by Von-Niessel and Hoffmeister in the 1920s (see the discussion in Lovell, 1954) for fireballs and by Opik (1941) who analysed the Harvard Arizona campaign suggested that a large proportion of Earth-impacting visual objects were extra-solar in origin.

The problem of assessing the reliability of such influx data rests primarily with velocity uncertainties: using the idea of an energy limit to fix Apex elongations and deduced Earth impact speeds, the precision required for speed could not be achieved using the techniques (like the ingenious rocking mirror method devised by Opik in the 1930s Harvard Arizona campaign) then available.

6.2. ORBITS

During the 1950s to 70s several photographic surveys were carried out using cameras of progressively advanced design culminating in the Baker-Super-Schmidts. To fix the atmospheric trajectories requires a stereoscopic arrangement – two (as a minimum) cameras spaced by 10–50 km being suitable. The system limiting sensitivity achieved was +3.5 (for the Baker Super Schmidts) stellar magnitude, equivalent to a particle of mass $\sim 10^{-2}$ g. Prominent among such surveys were those carried out by the Harvard College Observatory (McCrosky and Posen, 1961; Hawkins and Southworth, 1961; Jacchia and Whipple, 1961).

6.3. ARCHIVED DATA

Much of the orbital data resulting from such surveys were archived by the IAU Commission 22 (Lindblad, 1995). Various analyses of these and other data sets aimed to establish the presence of an extra-solar meteoroid component expressing results in terms of the proportion of unbound solar orbits relative to the cometary-asteroidal (IPD) source population. Much of the emphasis in such data-set examinations focussed on the orbital statistical validity. Examination of the archived material covering a variety of observational techniques presented the fraction of meteoroids having energy in excess of the parabolic limit: the fraction varied with technique and analysis stringency from 0.2% to 22%. The emphasis in some reports on the low percentage of hyperbolic orbits rather obscures the fact that even a minute proportion has important consequences. The expected contribution from ISD is small compared with the foreground dense dust cloud so that meteor inflow measurements on the Earth are necessarily dominated by the overwhelming flux of particles making up the solar system dust cloud. Depending on the uncertainties in orbit determination, a true extra-solar minor component may be mistaken for an outlier of the major population – particularly if no other parameter (e.g. directional) is simultaneously available.

The hyperbolic meteoroid orbit contribution discussed in surveys did not usually address the question of the orbit geometry or possible sources. The question of the statistical significance of the measured orbit – the uncertainty of the elements – remained. For example, the problem of fixing the pre-entry speed in terms of the observed speed in the atmosphere requires the use of either a reliable model of deceleration behaviour or the use of directly measured speed changes (and noting that for a given meteoroid, the deceleration is not constant throughout the ablation interval).

7. Recent Work on Orbits and Possible Sources

7.1. ELECTRO-OPTICAL

Such photographic, image intensifier, CCD systems have limiting magnitudes of about +8 (mass $\sim 10^{-4}$ g with the Mount Allison University group (Hawkes et al., 1997, 1999) and the University of Western Ontario group (Sarma and Jones, 1985) measuring a small but significant inter-stellar component.

7.2. RADAR

Because of the low expected terrestrial flux of ISD at 1 AU any technique that has the potential to acquire a large database of orbits is favourably

placed to establish the extra-solar contribution and delineate dust sources. Radar techniques offer such a capability with their capacity for continuous diurnal monitoring and sensitivity over electro-optical methods. Two geometries may be employed. Radial geometry scattering using a single narrow ($\sim 1^\circ$) wide radiation pattern with the ionisation created in the immediate vicinity of the ablating meteoroid (the head plasma) provides the radar reflection and the motion of the meteoroid is radial to the radar. Only a single radar employing one transmit-receive unit is required. If the aspect angle of the meteor trajectory to the beam central direction can be fixed, either by pulse-by-pulse positioning (as in e.g. the ALTAIR system Hunt et al., 2001) or using range-bin dwell time (e.g. Arecibo system Meisel et al., 2002) then the downstream direction of the ablating meteoroid can be fixed (to $\sim 1^\circ$).

In an alternative arrangement, the reflection geometry is arranged so that radar scatter takes place over a substantial length of the ionisation column. In this transverse geometry mode the meteoroid trajectory is orthogonal to the radar line-of-sight providing substantial reflection from the phase addition of contributing sections along the trail: the meteor downstream direction is located in a direction orthogonal to the echo reflection point direction. Multiple sites (a minimum of three) are required to fix the atmospheric trajectory. The total scattered energy in the transverse geometry comes from a region having a length of approximately one Fresnel zone length, $(R\lambda/2)^{1/2}$ (with R range and λ radar wavelength): the reflection geometry is similar to Fresnel diffraction at a straight-edge in the optical case. This compares with the head echo plasma size in the radial scatter geometry of a few metres so the transverse geometry echo cross-section is $\sim 10^3$ greater than the radial case. This gain in sensitivity provided by the transverse target geometry can be compensated to some degree by the antenna gain improvement provided by the use of a narrow pencil beam available with a large paraboloid and the transmitter power available with some radial geometry facilities.

7.2.1. *Arecibo*

The Arecibo 450 MHz facility uses the radial reflection geometry technique employing the large radio astronomical dish constructed within a natural topography feature and has an antenna beam directed in the general direction of local zenith (sterable) narrow enough to sense the inflow direction. The facility has been employed in searches for ISD with Meisel et al. (2002) reporting $\sim 2\%$ interstellar presence and indicating a supernova as a possible source. This incisive instrument, if able to delineate aspect angles and able to secure a statistically good database, should provide valuable evidence of ISD.

7.2.2. AMOR

This continually operating surveillance HF system employing transverse geometry is in a favourable situation to establish ISD inflow for large (compared to *in-situ* detections) grains. The AMOR (Advanced Meteor Orbit Radar) facility operates at a radio quiet geographical location in New Zealand transmitting 100 kW sampling rate 379 s^{-1} using an operating frequency of 26 MHz. The low frequency of operation combined with narrow beam (1.6° HPFW on transmitting) antennas enables a limiting sensitivity of $3 \times 10^{-7} \text{ g}$ (at speed 40 kms^{-1}). At the control-transmit site three antennas forming a dual base interferometer provide independent phase signals yielding echo elevation (to $\sim 0.3^\circ$) and signals for the pre- t_0 and Fresnel Transform meteoroid scalar speed measurements (see Baggaley and Grant, 2005 this volume). Two remote sites distance $\sim 8 \text{ km}$ and forming an approximate right-angled triangle receive reflections from different positions on the ionization trail using similar narrow beam antennas: FM UHF links then transmit the echo data to the central control site. This geometry allows the time-of-flight orthogonal velocity components to be fixed. Verification of the scalar speed produced by the echo timing is carried out by comparison with the phase information at the control site. Regular interrogation of the radar operation and rapid processing of downloaded echo signal data achieve about 90% uptime over several year's operation allowing some 10^6 individual orbits to be archived.

For any radar system, to secure the true distribution of heliocentric orbits, several observational corrections are necessary: the plasma density production dependency on meteor speed; the plasma geometry; the radar response function including antenna coverage of the celestial sphere; and the Earth collision probability for a given impacting body with specified orbital elements. AMOR has provided orbital distributions of the solar-bound dust cloud accessible at 1 AU (Galligan and Baggaley, 2004) for comparisons with the different sampling provided by dust *in-situ* detections and light-scattering methods using space-probes.

The database provides a sufficiently dense orbital element space that mapping of the extra-solar grains can be achieved. A significant feature of the orbital distribution found by AMOR is the change in velocity distribution characteristics with eccentricity, e . The de-biassed inclination distribution of orbits is quite different for well bound orbits – those with heliocentric speed < 38 – compared with those in the transition region ($\sim 38\text{--}44$) and those preponderantly unbound of $e > 1$ (Baggaley, 1998). The largely prograde closed orbits contrasts with the more uniform distribution (a cosine dependency is expected for a random directional inflow) for $e > 1$.

The heliocentric orbital characteristics of a solar-external stream of ISD are quite distinct. In ground-based detection of solar bound annual meteoroid streams – cometary or asteroidal – the Earth passes through a confined

stream in a matter of a few days: the observed orbital elements of the population cluster around a set of values (having, in the case of origins in e.g. young comets, some residual association with the parent comet). For a stream external to the solar system it is important to know what type of heliocentric orbits would intersect the Earth: what signature would indicate an unbound influx (irrespective of the ground-based technique employed for meteor detection). The geometrical property to address is the behaviour in the solar neighbourhood of inflowing ISD on Kepler orbits. For a collimated stream of ISD particles of lateral dimension large compared with the solar system flowing into the inner solar system – what would be the characteristics of the Earth-impacting orbits? In contrast to the annual cometary streams an external largescale stream of ISD would be present all year with characteristic seasonal cyclic variations in orbital elements, geocentric speed and observed flux. We can distinguished two types of Earth encounter: a type 1 collision when an ISD particle impacts the Earth at its first (and perhaps only) node crossing and a type 2 collision when an ISD particle encounters the Earth at its second node crossing. As illustration Figure 1 (from Baggaley and Nuslusan, 2002) shows the expected behaviour using a source having a far-Sun

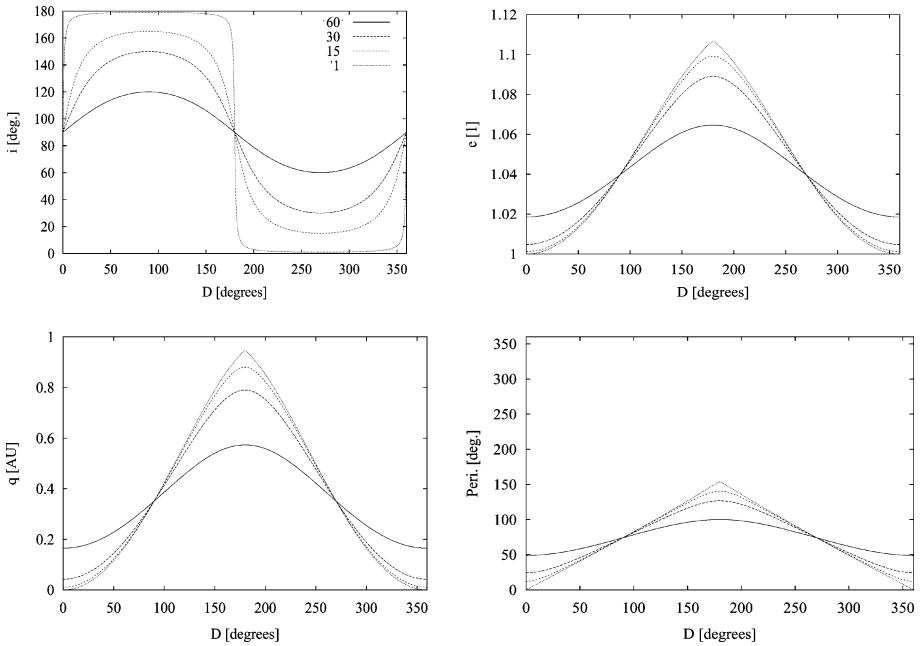


Figure 1. The changes in orbital inclination, i (upper left), eccentricity e , (upper right), perihelion distance q (lower left) and argument of perihelion, w (lower right), with longitude, D for type 2 Earth collisions for selected source latitudes β and $V_{\text{inf}} = 20 \text{ km s}^{-1}$. D is the difference between the ecliptic heliocentric longitudes of the Earth and external source.

heliocentric speed (for example) V_{inf} of 20 km s^{-1} and type 2 collisions: those signatures are valuable to distinguish extra-solar streams. The important feature is the quite different behaviour expected of extra-solar stream compared to a bound stream. In this way the seasonal cyclic behaviour of the observed orbital elements can be used to identify extra-solar streams and fix their far-sun inflow directions.

Using archived AMOR orbital data and from the heliocentric geometry the inflow directions of those particles with hyperbolic orbits can be mapped. From the heliocentric orbit, the upstream direction can be fixed by the asymptote – the tangent to the conic – which represents the direction in space from which the ISD approaches the solar system. Such a map using several years data of $\sim 5 \times 10^5$ orbits shows the solar-bound and unbound heliocentric inflow directions (Baggaley, 2004) in ecliptic coordinates. Two features are evident – a general inflow of ISD at southern latitudes and a more discrete feature at ecliptic $\lambda \approx 260^\circ, \beta \approx -58^\circ$ indicating a localized interstellar source. A significant property of that localised features is the energy distribution: the distribution of heliocentric speeds of those ISD within 15° of the mean direction shows a peak at $\sim 46 \text{ km s}^{-1}$ (far-sun speed of 11 km s^{-1}) (Baggaley 2000, 2004). The important feature of this finding is that two pieces of evidence for ISD are available – energy (which is the parameter considered in data analyses that focused on speeds in Section 6 above) and orbital characteristics (geometry).

8. Future Directions

An exciting mission is the proposed DUNE: a solar orbiting dust telescope placed in the $L_{1,2}$ position designed with a complex of multiple grids (in contrast to the two grids arrangement used in the impact detectors employed on e.g. Cassini) to fix grain trajectory to $\sim 1^\circ$ and obtain mass spectrometer data (see Grün et al., 2001). Ground-based orbital surveillance by especially radar is a valuable tool providing large data sets for the mapping the dynamics of the larger interstellar grains.

9. Summary

For an understanding of the dominating processes that control Galaxy evolution, an important task is to fix the mass fraction of solid material in interstellar space and also the important pathways of its recycling from stellar sources to incorporation into planetary systems. Measurements made within the solar system of fluxes, mass distributions, dynamics, chemistry and source directions will provide information on past and present relations with the

LIC, dark dusty clouds and giant molecular clouds, chemical isotopic and physical structure and evolution. Inside the solar system contemporary grains can be accessed via spacecraft impacts, by sample Earth return (providing chemical and isotopic analyses), by ground-based electro-optical and (especially) radar sampling providing precise dynamical data. In addition we may seek primordial grains – inclusions in meteorites, accumulations on body surfaces in the outer solar system that await collection. The paucity of ISD forces us to operate campaigns that will provide statistically useful data – for both spacecraft for small particles and for larger meteoroid earth impact.

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DEVELOPMENT OF AN ADVANCED DUST TELESCOPE

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Abstract. There are different types of dust particles in interplanetary space, such as dust from comets and asteroids, and interstellar grains traversing the solar system. Based on experience with current space dust instruments, a novel dust telescope is being developed. A dust telescope is a combination of a dust trajectory sensor for the identification and an analyzer for the elemental composition of the dust. Dust particles' trajectories are determined by the measurement of the electric signals that are induced when a charged grain flies through a position-sensitive electrode system. The objective of the trajectory sensor is to measure dust charges in the range 10^{-16} – 10^{-13} C and dust speeds in the range 6–100 km/s. First tests with a laboratory setup have been performed. The chemical analyzer will have an impact area of 0.1 m². It consists of a target with an acceleration grid and a single-stage reflectron for energy focusing, and a central ion detector. Results from SIMION simulations show that a mass resolution of $M/\Delta M > 150$ can be obtained.

1. Types of Dust in Interplanetary Space

The most obvious sources of interplanetary dust are comets, which move on highly eccentric orbits through the solar system. Gas pressure from the sublimation of volatile ices in the nucleus emits dust grains into space. Dusty tails of particularly bright comets can sometimes be observed with the naked eye (e.g., comet C/1995 Hale-Bopp). The larger dust particles obtain heliocentric orbits that are similar to the parent comet, thus, forming cometary trails (Sykes and Walker, 1992). Although dust is concentrated along cometary trails, most of the dust gets contiguously distributed in interplanetary space by planetary perturbations, collisions, and by the Poynting-Robertson effect.

Apart from cometary dust, a significant fraction of meteors and dust grains in the zodiacal cloud have their origin in the asteroid belt. Impacts of dust particles onto asteroids, and mutual collisions generate fragments covering a very wide size distribution. The composition and structure of dust particles from asteroids is expected to reflect that of the parent bodies, with much of the dust being silicate and iron-rich material. Their orbits have low inclinations and become more and more circular, which allows for a distinction from fresh cometary dust, which moves on highly eccentric orbits.

So far, a clear identification of the origin of cosmic dust near the Earth was not possible. Especially, the origin of interplanetary dust particles (IDPs) collected in the Earth's stratosphere and extracted from antarctic ice is still unclear. These are the only cosmic dust grains that are currently accessible for laboratory analysis. By simultaneously measuring the particles' trajectories in space and their chemical composition, we will search for criteria to distinguish cometary from asteroidal dust grains.

Most material contained in the Earth and the other planets has resided in galactic interstellar dust grains (ISD) 5×10^9 years ago before it was mixed and altered during the planetary formation process. Galactic dust is believed to originate in a variety of different stars and stellar phenomena e.g., carbon-rich stars, red giants, or supernovae, all of which provide dust with characteristic but different chemical and isotopic signatures that get modified during its passage through interstellar space (Dorschner and Henning, 1995). Based on isotopic analyses, a variety of presolar grains have been identified in primitive meteorites e.g., diamonds, graphite, silicon carbide, or corundum grains (Zinner, 1998). The identified grains constitute only a minute fraction of the total material that went into the protoplanetary disk. The composition of the bulk of the grains is largely unknown.

Galactic dust grains passing through the planetary system have been positively identified by the dust detector on board the Ulysses spacecraft (Grün et al., 1994). After its fly-by of Jupiter, Ulysses detected a flow of dust

particles predominantly from a direction that was opposite to the expected impact direction of interplanetary dust grains and with impact velocities that exceeded the local solar system escape velocity. Analysis showed that the motion of the interstellar grains through the solar system was parallel to the flow of neutral interstellar hydrogen and helium gas, both traveling at a speed of 26 km/s. The interstellar dust flow persisted at high latitudes above the ecliptic plane, where interplanetary dust is strongly depleted.

2. Measurements of Interplanetary and Interstellar Dust Grains

The flux of submicron to millimeter-sized dust in interplanetary space has been determined by dust detectors, and by crater counts on satellite surfaces and on lunar samples (see Grün et al., 1985 and Love and Brownlee, 1993). The size distribution of interplanetary dust is compatible with observations of zodiacal light, thermal infrared, and meteor observations (Divine, 1993). The expected impact rate on dust detectors at 1 AU is low, e.g., an impact detector of 0.1m^2 sensitive area records only about one particle of 10^{-13} g ($0.2\mu\text{m}$ radius) per day and one particle of 10^{-10} g ($2\mu\text{m}$ radius) per two weeks, respectively.

Any meteoroid in interplanetary space is electrically charged. Because of the predominance of the photoelectric effect in interplanetary space, meteoroids are usually charged at a potential U of about $+5\text{ V}$ (Morfill et al., 1986). In the near-Earth environment (LEO), the low energy plasma prevails, leading to dust grain potentials of about -0.5 V , whereas in the highly variable high energy plasma regime at geostationary distance, dust potentials from -30 V to $+3\text{ V}$ are expected. The charge q of a dust particle of mass m at a surface potential U is $q \propto \epsilon_0 U m^{1/3}$, where $\epsilon_0 = 1.1 \times 10^{-12}\text{ Vm/C}$ is the permittivity. It was Cassini's CDA instrument that, for the first time, reliably identified this charge ($\geq 10^{-15}\text{ C}$ corresponding to $\sim 2\mu\text{m}$ radius) on several interplanetary dust grains (Auer et al., 2002; Kempf et al., 2004). From the signal, the speed and impact direction could be determined. Furthermore, results of the Goro mission are essential in order to investigate dust charges in the Earth's orbit.

Compositional analyses of cometary dust have been achieved by the dust mass analyzers, PIA and PUMA on board space probes to comet Halley (Kissel, 1986). The instruments employed a time-of-flight mass spectrometer in order to obtain the elemental composition of the plasma generated upon the impact of cometary dust particles onto the sensor. A mass resolution of $M/\Delta M > 100$ was achieved by the use of a reflectron that provided energy focusing. Because of the very high dust fluxes expected near the comet, only a very small sensitive area of 5 cm^2 was necessary to obtain thousands of high-resolution dust mass spectra. The data collected by PIA/PUMA demonstrate

that each individual event detected contains a wealth of scientific information. It was found that the abundances of elements more refractory than O resemble solar composition and the composition of C1 chondrites alike (Jessberger and Kissel, 1991).

The Stardust spacecraft carrying the Cometary and Interstellar Dust Analyzer instrument, CIDA, flew by comet Wild 2 in 2004. CIDA, too, is an impact mass analyzer employing a reflectron stage in order to provide high resolution ($M/\Delta M > 100$) mass spectra. The sensitive area of this instrument is 90 cm^2 . CIDA provided compositional analyses of a few tens of cometary (Kissel et al., 2004) and of presumably interstellar grains (Krueger et al., 2004). Krueger et al. (2004) conclude that the main constituents of interstellar grains are organic, with a high oxygen and low nitrogen content.

A medium-resolution ($M/\Delta M \sim 20\text{--}50$) impact mass spectrometer of 100 cm^2 sensitive area is part of the Cassini CDA instrument. On its way to Saturn, it has measured several impact spectra of interplanetary or interstellar dust particles, and in the vicinity of Jupiter and Saturn, many hundred spectra of stream particles (Kempf et al., 2005).

3. The Dust Telescope

Based on experience with current space dust instruments, a novel dust telescope is being developed. The dust telescope is a combination of a dust trajectory sensor and a mass analyzer. It will provide a ten-fold increased sensitivity of charge detection over CDA's sensitivity and an increase of the sensitive area of dust compositional analyzers by at least a factor of ten such that even in interplanetary space statistically significant numbers of impact spectra from dust grains can be obtained.

3.1. DUST TRAJECTORY SENSOR

Dust particles' trajectories are determined from the charges induced in sensor electrodes by charged dust grains. The trajectory sensor measures dust charges $\geq 10^{-16} \text{ C}$ and allows us to determine trajectories of submicron-sized grains with accuracies of $\sim 1^\circ$ in direction and $\sim 1\%$ in speed.

A trajectory sensor to be used in dust accelerator tests has been set up (Figure 1). It consists of four sensor grids mounted between two electrical shielding grids (Srama et al., 2004b). Each sensor grid consists of 15 parallel wire electrodes (wires separated by 20 mm), each electrode being connected to a separate charge-sensitive amplifier (CSA). The wire directions of adjacent sensor grids are orthogonal. The distance between the grid planes is 40 mm. Each pair of adjacent wire electrodes within a sensor grid acts as a

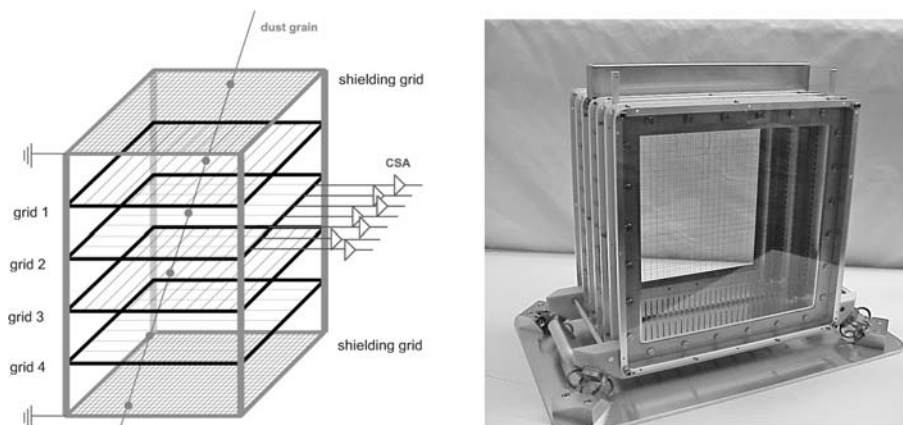


Figure 1. Left: Dust trajectory sensor schematics. It consists of four grids with 15-wire electrodes each and two shielding grids. Right: Laboratory model with an active area of 320×320 mm.

one-dimensional position-sensitive detector: The wire that senses the highest induced charge is closest to the dust particle's trajectory. Neighboring wires sense lower charges. The ratios of charge amplitudes yield the exact coordinate of the grain's location of passage through that grid plane (Auer and von Bun, 1994). Accuracies of 0.1° in direction and 0.1% in speed have been demonstrated with dust particles from the Heidelberg dust accelerator facility (Auer, 1996).

Key elements of the trajectory sensor are the CSA and the transient recorder. Two approaches are being studied: an application-specific integrated circuit (ASIC) version developed in cooperation with the Kirchhoff Institute for Physics of the Heidelberg University, Germany and a version made from discrete electronic parts and commercial components. So far, tests have been performed only with the ASIC version (Figure 2). It consists of two individual chips (Srowig, 2004). The front-end chip contains the CSA and a logarithmic amplifier for the compression of the dynamic range from 10^{-16} – 10^{-13} C. Its rms noise performance is 1.5×10^{-17} C (100 electrons) in a bandwidth from 10 kHz to 10 MHz. The transient recorder chip has 32 channels of analog–digital converters (ADC) with an accuracy of 10 bits at a 20 MHz sampling rate and 32 digital pipelines. A pipeline is a synchronous SRAM ring-buffer for 50- μ s trigger latency. An external trigger signal (e.g., derived from the dust impact onto an impact detector placed behind the trajectory sensor) stops the recording and all data is serially read out.

First, dust accelerator tests at the Max Planck Institute for Nuclear Physics, Germany have been performed with the described setup. A network of 30 front-end microchips and one transient recorder chip were integrated with the sensor. Figure 3 shows signals from particles passed at 1.5 mm from

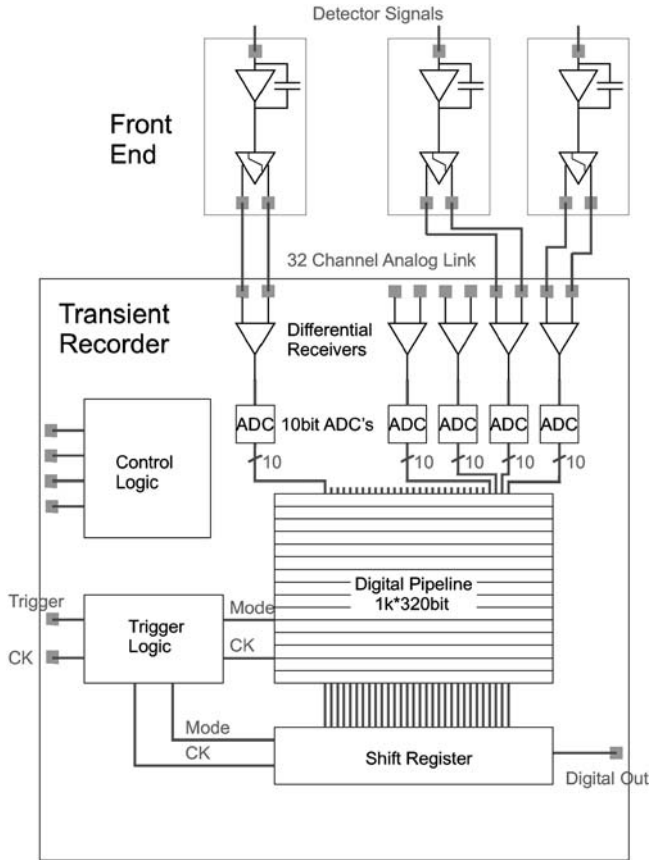


Figure 2. Trajectory sensor electronics consists of two ASICs: The front-end (CSA and log-arithmetic amplifier) and the transient recorder (32 channels with 10 bit ADCs and 1-K sample SRAM).

the closest electrode wire. Signals recorded in planes 1 and 2 are shown. Not only did the electrodes closest to the flight path respond, but also, more distant electrodes recorded significant signals. The tests were performed with iron particles with speeds between 4 and 30 km/s (0.1–1 μm grain size).

3.2. LARGE AREA MASS ANALYZER

The task of developing a large-area mass analyzer (LAMA) was to find a configuration that meets the requirements of a sensitive impact area of 0.1 m^2 and a mass resolution of $M/\Delta M \geq 100$. The main tool to model and analyze the large-area mass spectrometer was SIMION, a software package developed by David A. Dahl at the Idaho National Engineering & Environmental

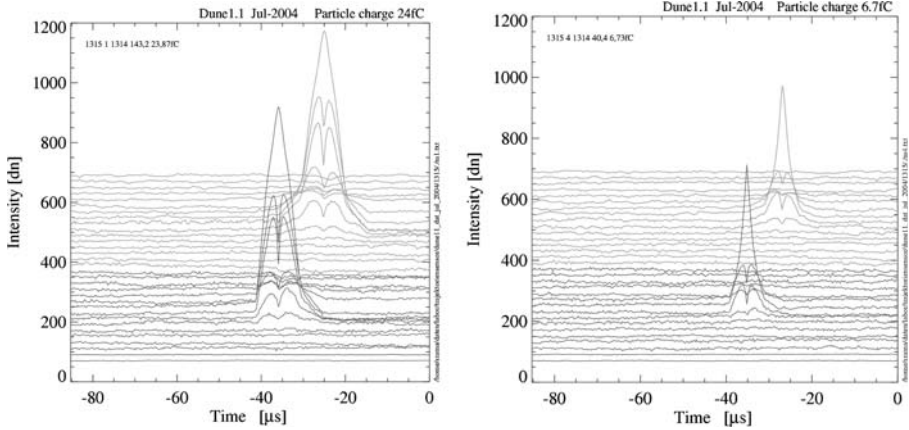


Figure 3. Trajectory sensor wire signals of a dust particle of two planes (*blue* and *red*). The impact occurred at time 0 and the closest wire distance was 1.5 mm. The sampling rate was 12 MHz. The linear range is between -100 and 250 dn for each channel relative to the baseline. The noise on the individual channels is close to 100 electrons. *Left*: Particle with 24 fC (broad peaks due to logarithmic amplitude compression). *Right*: Particle with a primary charge of 7 fC.

Laboratory, USA. This software allowed us to model complex structures and calculate the electric field distribution inside, and to determine ion trajectories and flight times (Rachev, 2004).

For LAMA, a configuration with cylindrical symmetry has been chosen with a ring-shaped impact target (Figure 4). The impact detector consists of an impact target at $+5$ kV potential and a grounded acceleration grid mounted 5 cm in front of the target. Potential rings provide a smooth electric field close to the edges. The acceleration distance of 5 cm is several times bigger than that for Cassini CDA (0.3 cm, Srama et al., 2004a) and Stardust CIDA (1 cm, Kissel et al., 2003). Thereby, the effect of shielding within the impact plasma cloud is reduced because the ion cloud is allowed to expand into a much wider volume before acceleration becomes effective.

In front of the impact detector, there is a field-free drift region of about 20 cm in length (in this space, a trajectory sensor can be introduced) and two parabolic reflectron grids (at 0 and approximately $+6,000$ V, respectively). Ion trajectories originating from different impact positions are shown in Figure 4. Ion trajectories are spatially and timely focused. It was assumed that ions have up to 50 eV energy spread and that they are emitted at different angles with respect to the target normal. An ion detector (microchannel plate) with a radius of about 120 mm will measure highly resolved spectra. The design is based on a configuration using hemispherical reflectron grids originally proposed by Oren and Svedhem (2000).

Parabolically shaped reflectron grids have been considered because of enhanced spatial focusing characteristics. Ions of varying starting positions at

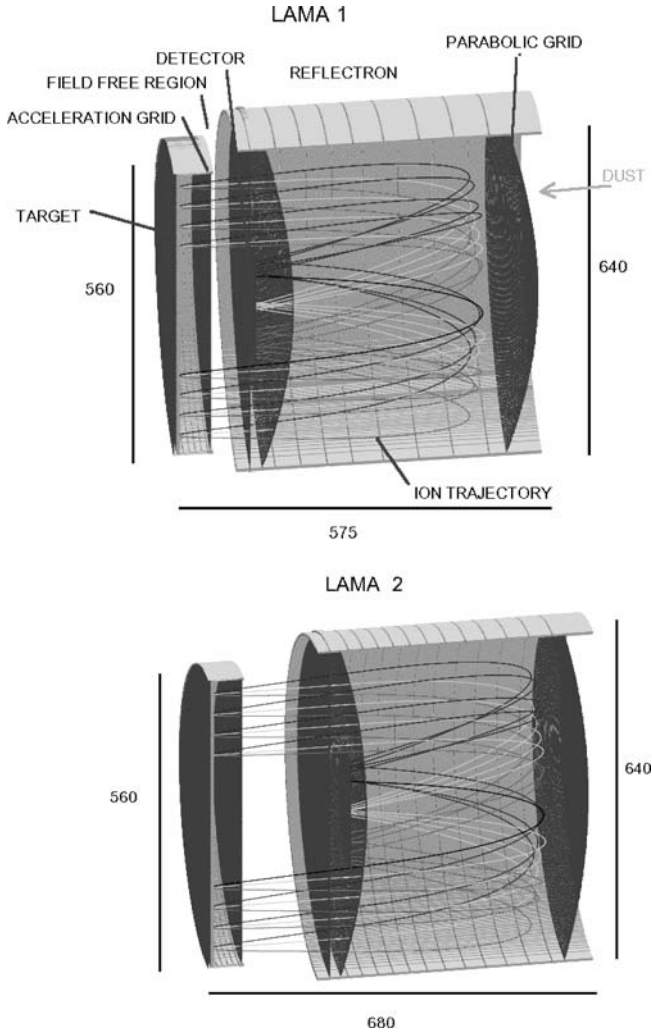


Figure 4. LAMA configuration schematics and cut-through of a SIMION 3D model. Ion trajectories calculated by SIMION are shown for four different dust impact positions at the target. Each position shows three trajectories: ion emission angle of -90° , 0° , and 90° relative to the target normal. The ion energy was set to 50 eV. The sensitive area of the ring-shaped target is 0.1 m^2 . The unit of the dimensions is mm. Top: LAMA1 (close target). Bottom: LAMA2 (target-reflector distance of 160 mm for an integration of a trajectory sensor).

the target, emission angles (0° – 90°), and energies (0–50 eV) are focused through the spectrometer. For a given potential of the upper reflectron grid, the axial position of the ion detector with optimum spatial focusing has been determined. After the ion detector position has been found for a given reflectron configuration, the distance of the impact detector and the potential of the reflectron grid are varied to find the optimum mass resolution. The

grid curvatures and the distance of the reflectron grids have been varied as well.

Several different configurations have been found that provide a mass resolution $M/\Delta M > 150$ for all impact locations on the target. We have chosen for initial tests to build a setup that allows us to easily combine the trajectory sensor with the LAMA. Simulations showed a mass resolution $M/\Delta M$ of better than 160 for all impact positions with a radius between 120 and 240 mm. However, the beam focus width at the ion detector plane reaches values of more than 200 mm.

4. Conclusions

There are different types of dust particles in interplanetary space: dust from comets and asteroids, and interstellar grains traversing the solar system. The identification of the source of a specific dust grain requires the determination of its orbital parameters and its elemental composition. This requirement leads to the development of a trajectory sensor and a mass analyzer with a sensitivity area of 0.1 m^2 . For the trajectory sensor, an integrated electronic readout circuit has been developed for multi-channel data processing. The low noise requirement (100 electrons) has been achieved. Complete system performance has been demonstrated with dust measurements at the dust accelerator in Heidelberg, Germany. A configuration for a large-area mass analyzer (LAMA) has been identified which achieves a mass resolution of $M/\Delta M > 150$ for dust impacts onto a sensitive area $> 0.1 \text{ m}^2$. A laboratory model of the LAMA is in the fabrication stage and will be tested in the next few months.

Acknowledgements

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A SEARCH FOR INTERSTELLAR METEOROIDS USING THE CANADIAN METEOR ORBIT RADAR (CMOR)

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Abstract. Using the CMOR system, a search was conducted through 2.5 years (more than 1.5 million orbits) of archived data for meteoroids having unbound hyperbolic orbits around the Sun. Making use of the fact that each echo has an individually measured error, we were able to apply a cut-off for heliocentric speeds both more than two, and three standard deviations above the parabolic limit as our main selection criterion. CMOR has a minimum detectable particle radius near 100 μm for interstellar meteoroids. While these sizes are much larger than reported by the radar detections of extrasolar meteoroids by AMOR or Arecibo, the interstellar meteoroid population at these sizes would be of great astrophysical interest as such particles are more likely to remain unperturbed by external forces found in the interstellar medium, and thus, more likely to be traceable to their original source regions. It was found that a lower limit of approximately 0.0008% of the echoes (for the 3σ case) were of possible interstellar origin. For our effective limiting mass of 1×10^{-8} kg, this represents a flux of meteoroids arriving at the Earth of 6×10^{-6} meteoroids/ km^2/h . For our 2σ results, the lower limit was 0.003%, with a flux of 2×10^{-5} meteoroids/ km^2/h . The total number of events was too low to be statistically meaningful in determining any temporal or directional variations.

Keywords: Interstellar, meteoroids, meteors, radar

1. Introduction

While previous experimental studies have provided flux estimates of interstellar particles (ISPs), they were limited to particles under 100 μm in radius. Flux estimates for larger dust in the interstellar medium (ISM) are unconstrained since there is no easy way to remotely sense the number density of these larger particles. The detection of such particles is also very important as larger particles are less likely to be perturbed by external forces found in the ISM, such as interstellar magnetic fields. This implies that they may be more readily associated with their original source regions or stars through back integration of their motion, and their larger sizes implies a longer survival time against collisions or shock disruption. This is important as the processes in which ISPs are produced and ejected into the ISM, particularly for larger particles, are not very well constrained. Knowing source regions, and the

possible detection of streams of ISPs at the Earth (cf. Baggaley and Neslusan, 2002) would allow for direct sampling (through aerogel capture), which would give the first opportunity to investigate the chemical and isotopic signatures of ISPs with a known origin. Measuring the space density of the largest ISPs is also important for estimating the mass density and gas-to-dust ratio of the ISM proximal to the solar system as most of the mass of the dust grains in the ISM is expected to be contained in the largest grains (Landgraf et al., 2000). While we are measuring the larger grains in the local ISM, it is important to note that these grains are dynamically decoupled from the local interstellar gas flow and hence, not directly physically connected to the Local Interstellar Cloud (Kimura et al., 2003).

Here we examine the flux of ISPs visible from the northern hemisphere using an all-sky, VHF orbital radar.

2. Previous Studies

The first modern detection of ISPs in the solar system was made by Ulysses in 1992 (and later confirmed by Galileo) when it detected a flux of micrometre-sized dust particles (Grün et al., 1993) moving in a retrograde orbit with heliocentric speeds above the solar system escape speed at Jupiter (26 km/s). These detections were the first to prove definitively that some ISPs do enter the solar system.

A search for interstellar meteoroids was conducted by Baggaley (2000) using the Advanced Meteor Orbit Radar (AMOR) located in New Zealand. Baggaley claimed to be able to identify the existence of a dust influx from a widespread south-ecliptic latitude source as well as a discrete stream that he identifies as being in the direction of the main-sequence debris-disk star β -Pictoris. As well, there have been also been reported detections from Arecibo (Meisel et al., 2002).

Murray et al. (2004) on theoretical grounds, show that for such large particles as will be considered here ($> 100 \mu\text{m}$), the ISPs can travel for tens of parsecs through the ISM without having their paths altered. This allows their source regions to be determined. They also give a rough estimate to the flux of ISPs that are expected to be visible at the Earth, as both a function of mass, and particle size. For CMOR, a particle size of $100 \mu\text{m}$ (assuming a meteoroid density of 3000 kg/m^3) should have a detectable ISP flux of approximately 5×10^{-4} meteoroids/ km^2/h , using a power-law relation extrapolated from the distribution of the largest mass ISPs detected by Ulysses and Galileo, as originally noted by Landgraf et al. (2000).

Hawkes and Woodworth (1997) used image-intensified camera systems to search for meteoroids of interstellar origin. Optical studies are advantageous in that the results are more accurate (due to a larger portion of the meteor

trail being visible), however the number of detected events can be quite small. Out of 160 observations, they found that two events, with masses on the order of 10^{-7} kg, were of interstellar origin. This represents 0.01% of their total observations.

Hajduková (1994) made a detailed study of photographically determined meteor orbits found in various catalogues, and determined that almost all of the hyperbolic orbits (which amount to 12%) were potentially due to errors in determination of their heliocentric speeds. When the errors were taken into account, the actual fraction of photographically determined orbits that may be of interstellar origin was reduced to be at most 0.002%. It is clear from this, that proper error analysis is essential in identifying ISPs.

3. Instrumentation and Data

The Canadian Meteor Orbit Radar (CMOR) is 6 kW peak power HF/VHF meteor radar based on the commercially available SKiYMET system (Hocking, 2001). The system, located near Tavistock Canada (43.264° N, 80.772° W) has been modified to include two additional remote station receivers used for time-of-flight velocity measurements, and has a radio magnitude limit of +8, corresponding to an effective limiting mass of 4×10^{-8} kg at typical interplanetary meteoroid encounter speeds. The system is further described by Jones et al. (2005). An important feature of CMOR is that it provides individual error estimates on all measured and derived quantities for each echo. This permits a more detailed examination of data on a case-by-case basis for high speed meteoroids, without the need to appeal to average errors in velocity. In fact, velocity errors measured by an orbital radar can have a strong geometry dependence, so individual error estimation is essential.

CMOR has been in multi-station operation since early 2002, with approximately 2500 meteoroid orbits determined each day. The total orbital dataset size is well over one million orbits. This study covers the time period between May 2002 and September 2004 with all radar downtime taken into account for the final flux calculations.

Each observed echo has an empirically derived estimate for atmospheric deceleration applied to compute an estimated out-of-atmosphere speed (cf. Brown et al., this volume for more details).

Individual meteor masses are estimated based on the mass–speed–electron line density relation developed by Verniani (1973). This mass estimate follows from the minimum electron line density computed in Ceplecha et al. (1998) and described more recently by Cervera et al. (2004). Specifically, each echoes electron line density is estimated taking into account antenna gain. We also note that our masses are lower limits as we implicitly assume the specular point also corresponds to the point of maximum ionisation.

4. Analysis

In order to have high confidence in the validity of any results obtained, a strict set of selection criteria was applied to the dataset. The first step was to select out only those meteoroids which had a heliocentric speed 3σ above the hyperbolic threshold.

The second step involved the direct verification of the fiducial points used in the time-of-flight velocity measurements. This was done by plotting the meteor amplitude as a function of radar pulse number for each meteor echo, and verifying by visual inspection that the fiducial points were determined correctly.

At present, the software regularly employed by CMOR to compute the apparent echo location in the sky may produce incorrect results due to the interferometric algorithm chosen. To account for this, the interferometry was recomputed using an independent, alternate technique, and only those echoes which agreed to the original values to within two degrees were accepted. This is comparable to the expected error in the interferometry (estimated to be on the order of 1°).

Lastly, there is a condition found in the reduction software that forces the meteor trail orientation to always point downward. In the unusual case of the apparent radiant appearing close to the horizon, the associated error in the radiant may cause the meteors to appear to be actually coming from below the horizon. In such cases, the radiant point is placed by the software on the opposite side of the celestial sphere, and in some cases, the orbit may become hyperbolic. This was observed, for example, in connection with the Quadrantid shower in 2003 and 2004, when the peak of that shower occurred as the radiant was just rising. To minimise this effect, all echoes having radiants within an angular altitude less than 1σ of the horizon were removed from the analysis.

This strict selection process makes any flux estimates a lower bound, since the actual number of interstellar meteoroids may be much higher. We also repeated the entire analysis procedure accepting all events within a 2σ error bound in heliocentric speed.

5. Results and Discussion

Of the initial 1556384 meteoroids, only 12 remained after all the selection criteria (for the 3σ case) were applied. It is worth noting again that these represent the lower limit of the total number of ISPs we may expect to detect. As well, after the horizon check, the final population shows no potential ISPs with radiant elevations below 6° .

This meteoroid count represents 0.0008% of the initial population. CMOR has a 2500 km² average daily integrated collecting area, which is calculated according to the technique described in Brown and Jones (1995). This allows a lower bound on the flux to be estimated at 6×10^{-6} meteoroids/km²/h, to an effective limiting mass of 10^{-8} kg. When the analysis was redone for the 2σ case, only 40 events remained, which represent 0.003% of the initial population. This provides an estimated flux of 2×10^{-5} meteoroids/km²/h. Both results are compared to the other observational results in Figure 1, which shows that the flux estimates for CMOR lie very close to a power law extrapolation. However, it is important to note again that the CMOR flux estimates for larger grains represent lower bounds, and the small dust detected by Ulysses/Galileo is of a different dynamical population.

For the 2σ results, the median out-of-atmosphere speed was found to be 56 km/s, and the median heliocentric speed was found to be 68 km/s.

Since the effective limiting error in heliocentric speed for our 2σ results is about 15%, we would expect all meteoroids with a true heliocentric speed greater than 55 km/s to be detected. This corresponds to a minimum pre-solar system encounter speed of 35 km/s. With young stars having pre-solar

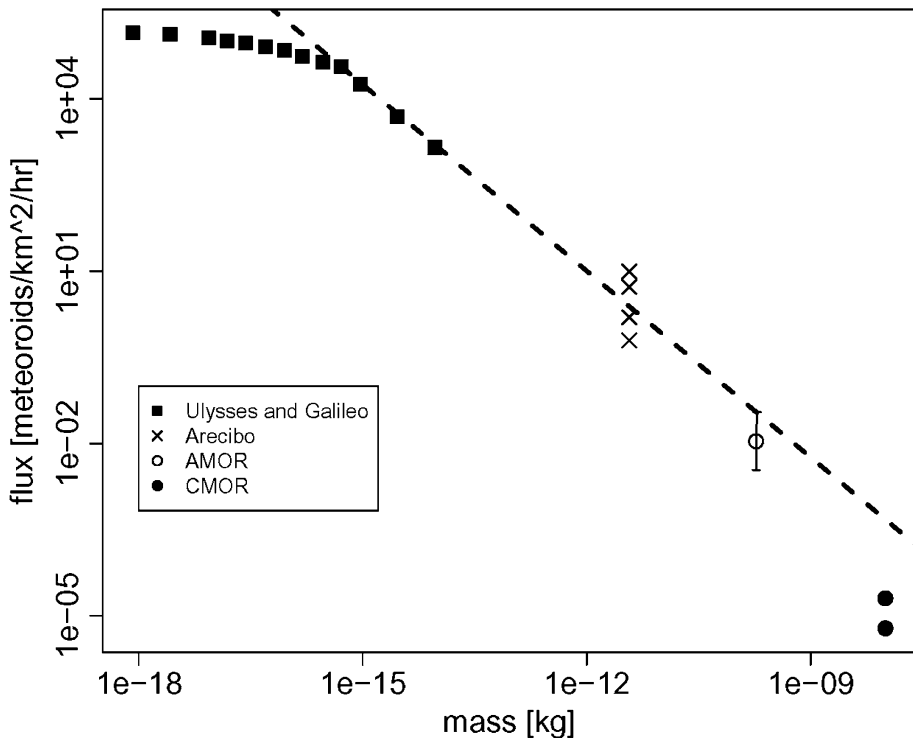


Figure 1. Comparison of flux estimates between various studies. The CMOR values represent lower bounds, with the top one being the 2σ result.

system encounter speeds on the order of 12 km/s (Murray et al., 2004), we are not surprised that there is no significant detectable flux of material in our mass range at these speeds. At ejection speeds larger than 90 km/s, as might be associated with polar outflows from YSOs (Murray et al., 2004), our expected measured atmospheric speed would be greater than 70 km/s, and would be heavily selected against due to initial radius attenuation.

Directional and temporal variations were also considered for the 2σ case. However, there were too few events to provide a statistically meaningful estimate on any potential source regions or outburst times.

6. Conclusions

It was found through a strict selection process of the CMOR orbital data that for an effective limiting mass of 1×10^{-8} kg, a lower limit flux of ISPs equal to 2×10^{-5} meteoroids/km²/h arrives at the Earth for our 2σ criteria. For our 3σ criteria, the lower limit flux is found to be 6×10^{-6} meteoroids/km²/h. This larger particle population is of interest for tracing material back to its source region, as these particles are less likely to be perturbed by external forces found in the ISM. Future work will focus on refinements in the data processing, dealing with the declination dependent collecting area instead of an average, and considering a 1σ error bound in the heliocentric speeds.

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COMPLEX OF METEOROID ORBITS WITH ECCENTRICITIES NEAR 1 AND HIGHER

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Abstract. In our work, the method that can help to predict the existence of distant objects in the Solar system is demonstrated. This method is connected with statistical properties of a heliocentric orbital complex of meteoroids with high eccentricities. Heliocentric meteoroid orbits with high eccentricities are escape routes for dust material from distant parental objects with near-circular orbits to Earth-crossing orbits. Ground-based meteor observations yield trajectory information from which we can derive their place of possible origin: comets, asteroids, and other objects (e.g. Kuiper Objects) in the Solar system or even interstellar space. Statistical distributions of radius vectors of nodes, and other parameters of orbits of meteoroids contain key information about position of greater bodies. We analyze meteor orbits with high eccentricities that were registered in 1975–1976 in Kharkiv (Ukraine). The orbital data of the Kharkiv electronic catalogue are received from observations of radiometeors with masses 10^{-6} – 10^{-3} g.

Keywords: Interplanetary dust, interstellar dust, meteoroids, meteor radar, orbits



The well-known Soviet and Ukrainian investigator of meteors Boris Leonidovich Kashcheyev.

1. Obituary

On 15 January 2004 Prof. B.L. Kashcheyev died. He was born on 8 March 1920. Sc.D, Prof. B.L. Kashcheyev provided guidance of meteor astronomical and geophysical researches of meteor centre of the Kharkiv National University of Radioelectronics (KHNURE) during 1957–2000. Prof. B.L. Kashcheyev was a member of International Astronomical Union (IAU) starting in 1958 after Kharkiv successful experiments during International Geophysical Year (IGY). He was a famous Soviet and Ukrainian scientist.

Prof. B.L. Kashcheyev made great contribution to the development of science and education in the KHNURE, and to the international investigation of meteors. In Minor Planet Circular IAU N 32346, 8 August 1999, there is the asteroid “Kashcheev” with N 6811 = 1976QP.

2. Introduction

The meteor centre of the KHNURE has almost semi-centennial experience in carrying out ground radar observation of faint meteors in Kharkiv (Kashcheyev and Tkachuk, 1980), and in the interpretation of the data from radar observations (Voloshchuk et al., 1989; Voloshchuk et al., 2002). The question on interpretation of the orbital data with eccentricities near 1 and higher is the least investigated. Research carried out in Kharkiv (Kashcheyev and Kolomiyets, 2001) gives much proof to existence of real hyperbolic orbits at 1 AU for meteoroids with mass $m > 10^{-6}$ g near the Earth. Modern researchers do not deny existence of real hyperbolic orbits in the Solar system. New populations of interplanetary dust at 1 AU are proposed (Dikarev et al., 2001) in the ESA meteoroid model: from micron-sized dust to meteoroids with mass $m > 10^{-6}$ g. Number of impacts during to measurements of Galileo and Ulysses dust detectors equals to sum the counts predicted by the interplanetary dust (IPD) population and the predicted counts taking into account the interstellar dust (ISD) population. Nevertheless, the problem of division into two populations (ISD and IPD) of registered orbits with $e \geq 1$ among the KHNURE data has not been solved yet.

3. Meteoroid dynamics in the ecliptic plane of the Solar system (two aspects of one search method)

The hyperbolic orbit in contrast to an elliptic one can have only one point of crossing with the ecliptic plane. For hyperbolic orbits having two nodes one can find perturbation forces in the ecliptic plane, which could give rise to transformation of their initial, probably, a non-hyperbolic orbit. The meteor orbits crossed with an orbit of any of planets, may be transformed, if in a point of crossing of their orbits or near to this point of crossing, the meteor particles and the planet appear in close contact. The results of modelling on an estimate of incoming to the Earth the flux of particles by hyperbolic orbits, appearing in the result of their initial orbital transformation in spheres of the planetary effect confirm the fact that any of planets of the Solar system is capable of performing such orbital transformation (Andreyev et al., 1993). For search of mentioned above crossed orbits the authors offered to use radius vectors of ascending and descending

nodes $R_{N,V}$, parameter of orbit p , argument of perihelion ω , eccentricity e , perihelion distance q . Theoretical parameters of orbits (with $e \geq 1$), which cross the ecliptic plane on the certain distance from the Sun, are given in the Table I. Calculation is executed on the basis of below mentioned formulas and assumptions:

So $R_{N,V} \cong r_P \pm \Delta r_P$, and $R_{V,N} \cong r_E \cong 1AU$, then $\pm e \cos \omega = \frac{R-1}{R+1}$.

For meteoroid orbits of the Solar system: $p = R_{V,N} (1 \pm e \cos \omega)$; $0.558 \leq p < 2$.

Put restrictions on a true anomaly ϑ : $tg(180 - \vartheta_{\max}) = \frac{p}{q}$ and $\vartheta \leq \vartheta_{\max}$; then for meteoroids observed on the Earth $\omega_V \leq \vartheta_{\max} \leq 116.6$ $63.4 \leq \omega_N$.

We mark $\omega_0 = |p - 1|$ and deduce following limitations.

For meteoroid orbits connected with inside planets ($p < 1$): $q \leq R_P$; $\omega_{V1} \leq \omega \leq \omega_{V2}$ (for ascending node V : $\omega_{V1} = 180 - \omega_0$, $\omega_{V2} = 116.6$) and $\omega_{N1} \leq \omega \leq \omega_{N2}$ (for descending node N : $\omega_{N1} = 63.4$, $\omega_{N2} = \omega_0$).

For meteoroid orbits connected with outer planets ($1 < p < 2$): $q \leq 1$; $\omega_{V1} \leq \omega \leq \omega_{V2}$ (for ascending node V : $\omega_{V1} = \omega_0$, $\omega_{V2} = 116.6$) and $\omega_{N1} \leq \omega \leq \omega_{N2}$ (for descending node N : $\omega_{N1} = 63.4$, $\omega_{N2} = 180 - \omega_0$).

4. Observational results

The application of this possible criterion has been checked on results of measurements in Kharkiv for data 1975–1976. Among the data of 1975 (1304 orbits with eccentricities near 1 and higher) 63% the orbits with two nodes have been found. Among them we founded orbits that had radius vectors of

TABLE I
Orbital parameters for searching meteoroid orbits with $e \geq 1$ that formed planetary perturbations

Planets	r_p , AU	p	q , AU	ω_{V1} , degree	ω_{V2} , degree	ω_{N1} , degree	ω_{N2} , degree
Mercury	0.39	0.558	0.379	116.2	116.6	63.4	63.8
Venus	0.72	0.840	0.420	99.2	116.6	63.4	80.8
Mars	1.52	1.208	0.604	78.0	116.6	63.4	102.0
Mainbelt asteroids	2.2	1.375	0.687	68.0	116.6	63.4	112.0
Mainbelt asteroids	3.6	1.524	0.762	58.4	116.6	63.4	121.6
Jupiter	5.2	1.678	0.839	47.3	116.6	63.4	132.7
Saturn	9.5	1.810	0.905	35.9	116.6	63.4	144.1
Uranus	19.2	1.901	0.950	25.7	116.6	63.4	154.3
Neptune	30.1	1.936	0.968	20.7	116.6	63.4	159.3
Pluto	39.4	1.951	0.975	18.1	116.6	63.4	161.9
Trans-Plutonian	1000	2.000	1.000	0	116.6	63.4	180.0

nodes $R_{V,N}$ are close to planet orbits r_p within distance in $\pm \Delta r$: 51 meteoroid orbits near the Mars orbit (1.52 AU), 42 meteoroid orbits near the Jupiter orbit (5.2 AU) and 35 meteoroid orbits near the Saturn orbit (9.5 AU). For choice we used parameters of Table I too. We founded 43 meteor orbits that had their nodes in the Kuiper–Edworth belts ($R_{V,N}$ from 40 till 10,000 AU) and farther. Thus we got confirmation of the migration of investigated particles to the Earth from the different belts of the ecliptic plane of the Solar system. In Figures 1–3, we can see statistical characteristics of meteor complex with high eccentricities (e near 1 and higher).

According Kharkiv data in 1976: $N = N(R_v, e)$ – Figure 1, $N = N(R_v, q)$ – Figure 2, $N = N(R_v, \omega)$ – Figure 3, where N – number of terms of selected groups with scale of grey shade (axis z); R_v – radius vectors of ascending nodes (axis x); e – eccentricity, q – perihelion distance and ω – argument of perihelion (axis y). Testing different place of the Solar system was made with using radius vectors of ascending nodes R_v (UA) of meteoroid orbits for division into formal groups: $0 < R_v < 1$ of 106 orbits; $1 < R_v < 5$ of 167 orbits; $5 < R_v < 50$ of 99; $50 < R_v$ of 17 orbits. In Figures 1–3 are demonstrated only qualitative pictures for investigating of the structure of picked orbital meteor complex with eccentricity near 1 and higher. Statistical distributions of radius vectors of nodes, and other parameters of orbits of meteoroids can contain key information about position and migration of greater bodies between different regions of the Solar System near the Sun and beyond.

Besides, for hyperbolic orbits, establishing an actual ejection by calculating the orbit backwards in time to see if the planet was actually near the supposed ejection point is much easier than for elliptical orbits. By

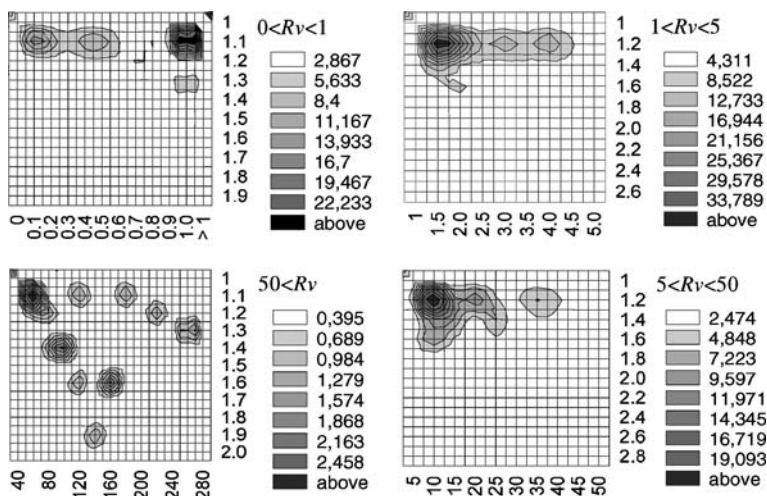


Figure 1. Radius vector of ascending node R_v (AU) against eccentricity e .

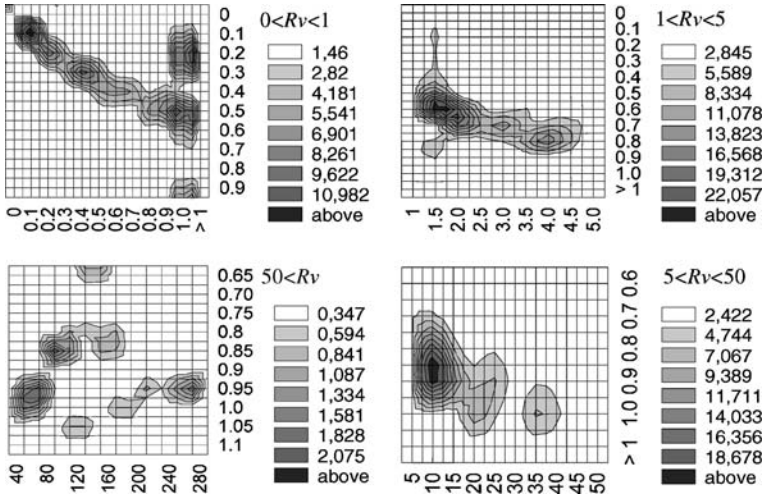


Figure 2. Radius vector of ascending node R_v (AU) against perihelion distance q .

calculating the orbit moving backwards in time we may select those observed meteoroids that had the contacts with planets. Here, to simplify a problem, we used the indirect method (Štohl, 1969) for searching hyperbolic contact individual orbits. The calculation by Štohl (1969) shows the expected dates on which the planet perturbed meteors might be observable for the different years. These calculated dates occur as the average on the 265th, 161st, 156th day after the opposition of Mars, Jupiter and Saturn, respectively. These dates are given for meteors for which the resulting orbit is parabolic. Hyperbolic

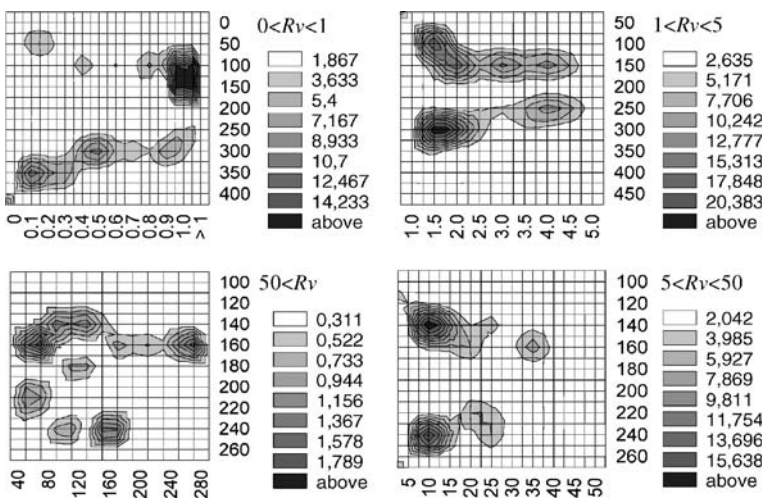


Figure 3. Radius vector of ascending node R_v (AU) against argument of perihelion ω .

orbits should be observable in short periods immediately preceding these dates. For example, 8 days for orbits (with eccentricities within the limits $1.0 < e < 1.1$) perturbed by the Mars. In that way checked orbits have been obtained among about 2000 hyperbolic orbits that observed in Kharkiv in 1975–1976. We selected 9 transformed orbits according their observed times (among 51, 42 and 35 orbits that mentioned above). There are 4 possible orbits formed by planetary perturbation of the Mars that registered close to 1976, September 7 (265th day after the Mars opposition on 15 December 1975). There are two possible orbits – near 13 February 1975 and one possible orbit – near 22 March 1976 (161st day after the Jupiter opposition on 5 September 1974 and on 13 October 1975). There are 2 possible orbits formed by planetary perturbation of the Saturn that registered close to 11 June 1975, and 25 June 1976 (156th day after the Saturn opposition on 6 January 1975 and on 20 January 1976). Their orbital parameters were published (Kashcheyev and Kolomiyets, 2001).

5. Conclusion

For research of the structure of the complex of meteor orbits with eccentricities higher or nearer to unit, observably on the Earth, it is possible to use orbital parameters – radius vectors of ascending or descending nodes. Division of the data on values of radius vectors of nodes allows to make formal assumptions of in what part of Solar system such particles may be basically.

6. Future works

The properties of the complex of the observed meteor orbits of the KHNURE catalogue (near 250,000 orbits with $e > 0$, including near 9000 orbits with $0.9 < e < 2.5$) can be used in searching and researching: (1) of the most “dangerous” unobserved parent bodies that have high heliocentric velocities and high eccentricities; (2) another unobserved NEOs (Near Earth Objects); (3) the interstellar dust (ISD) population and interplanetary dust (IPD) population; (4) distant objects in the Solar system.

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OPTICAL PREDICTIONS FOR HIGH GEOCENTRIC VELOCITY METEORS

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Abstract. In this study we numerically modelled the atmospheric ablation and luminosity of cometary structure meteoroids with geocentric velocities from 71 to 200 km/s. We considered meteoroid masses ranging from 10^{-13} to 10^{-6} kg. Expected heights of ablation and maximum luminosity absolute magnitudes are determined. Height and trail length values are used to calculate the angle traversed in a single video frame. It is found that for pre-atmospheric meteoroid masses of greater than 10^{-8} kg, high geocentric velocity meteors should be detectable with current electro-optical technology if properly optimised.

Keywords: Ablation, high velocity, interstellar meteoroid, meteor, optical detection

1. Introduction

There exist several mechanisms such as stellar radiation pressure and dynamical N-body processes for injection of high speed meteoroids into interstellar space (Hawkes and Woodworth, 1997; Murray et al., 2004). A recent study by Quirt and Hawkes (2005) suggests that in some cases small meteoroids may be ejected from pre-main sequence stellar systems by radiation pressure with velocities on the order of several hundreds of km/s. While destruction and velocity alteration processes in interstellar space (see e.g. Jones et al., 1997; Murray et al., 2004) may mean that very few of these meteoroids would survive to Earth with their velocities intact, the possibility of a small population of high geocentric velocity meteoroids remains. Although there is some evidence for the detection of high geocentric velocity meteors by radar (Taylor et al., 1996), meteors having geocentric velocities in excess of 80 km/s have not been conclusively observed by electro-optical methods. In this paper, the ablation heights and luminosities of high geocentric velocity meteors in the Earth's atmosphere are predicted.

2. Computational Model

A single body, isothermal, cometary structure meteoroid in the free molecular flow regime experiencing thermal meteoroid ablation was assumed. Meteoroid masses ranging from 10^{-13} to 10^{-6} kg in increments of 10, and initial meteoroid velocities of 71, 80, 90, 100, 125, 150, and 200 km/s were considered. A fourth order Runge-Kutta method with a semi-adaptive step size was employed to numerically solve the system of coupled differential equations describing meteoroid flight through the atmosphere. For more information on the equations of thermal meteoroid ablation and the physical as well as thermal meteoroid parameters assumed, please see Appendix A. Averaged data from various months from the NASA MSISE 90 model (Hedin, 1987, 1991) were employed to develop a profile of the atmospheric mass density with altitude (details of the numerical fit are outlined in Rogers et al., 2005).

The luminous efficiency factor, which relates meteor light intensity to incident kinetic energy, is one of the least conclusively established values in meteor physics, particularly at high velocities. In this work the dependence of luminous efficiency on velocity is based on relationships developed by Jones and Halliday (2001). They used atomic collision theory for predicting the dependence of luminous efficiency factor on velocity (through an intermediate quantity, the excitation coefficient). While their results are only strictly applicable to velocities below 46 km/s, they found that an extrapolation to 60 km/s yielded excellent agreement with observations. Based on this agreement, they extrapolated their values of excitation coefficient to 100 km/s. We applied a further linear extrapolation of their excitation coefficient from 100 to 200 km/s. This means that we have less confidence in the values obtained for velocities above 100 km/s (the height and trail length data are not dependent on the luminous efficiency value). A detailed account of the equations of the assumed luminous efficiency factor can be found in Hill et al. (2005). The values of the luminous efficiency factor employed here are presented in Table I. The corresponding values given by the linear increase of luminous efficiency with velocity as suggested by Whipple (1938) and Verniani (1965) are provided for comparison.

TABLE I
Luminous efficiency used in this work, and as proposed by Verniani

velocity (km/s)	71	80	90	100	125	150	175	200
τ_1 (this work)	0.0076	0.0064	0.0054	0.0046	0.0033	0.0025	0.0020	0.0017
τ_1 (Verniani)	0.0037	0.0042	0.0047	0.0053	0.0066	0.0079	0.0092	0.0105

3. Results

The dependence of maximum light intensity (expressed in absolute meteor magnitude) on velocity is given in Figure 1. Only a very slight increase in peak light intensity with velocity occurs, despite the increase of the kinetic energy of the ablated meteoric particles proportional to the square of velocity. This is due to the decay of the extrapolated luminous efficiency at high velocities.

The heights where the meteors reached their peak brightness (displayed in Figure 2) are largely independent of the luminous efficiency factor. As anticipated, the ablation heights decrease with increasing mass. They are also shown to increase with velocity, for example a 10^{-8} kg meteoroid with an initial velocity of 100 km/s reaches its maximum brightness at an altitude of 116 km while a similar meteoroid having an initial velocity of 200 km/s reaches its peak at 135 km.

4. Observational Implications

In Table II the times for which each of the modelled meteors was brighter than $+8^M$ are presented. A light intensity of $+8^M$ was chosen as a representative limit of detection for sensitive electro-optical equipment. If a meteor had such a high angular velocity that it could only be detected in a single frame an accurate determination of its velocity would be impossible and even detection could be substantially compromised. It can be seen from Table II that high geocentric velocity meteors having pre-atmospheric masses of at

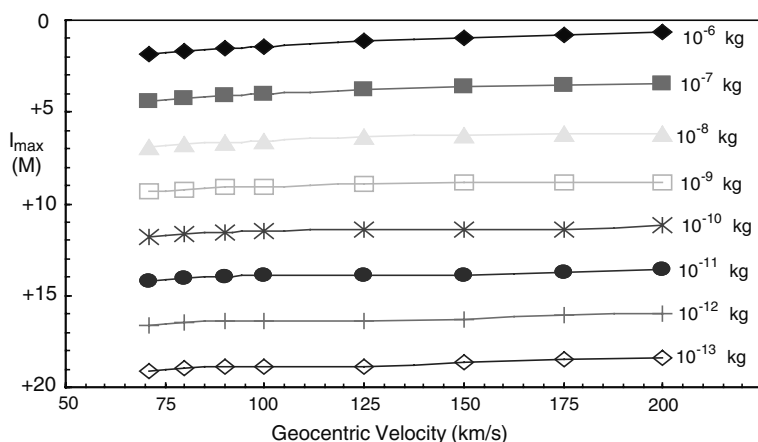


Figure 1. Plot of the peak luminous intensity (expressed as absolute meteor magnitude) versus the geocentric velocity (in km/s).

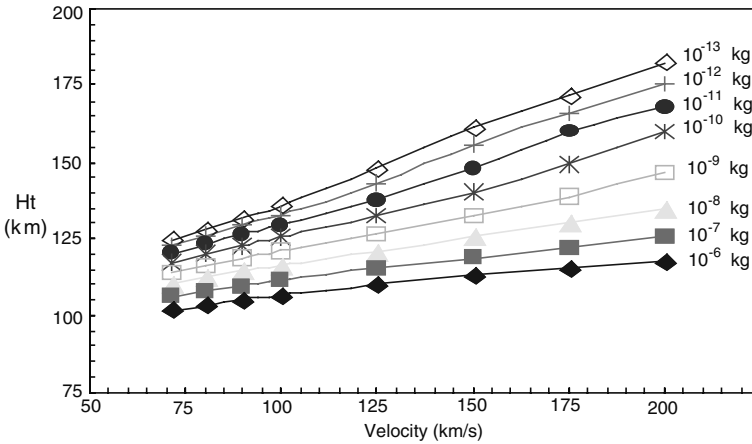


Figure 2. Plot of height of maximum intensity (in km) versus the geocentric velocity (in km/s).

TABLE II
Times (s) for which meteors are brighter than $+8^M$

velocity (km/s):	71	80	90	100	125	150	175	200
10^{-6} kg	0.379	0.354	0.333	0.317	0.294	0.286	0.285	0.286
10^{-7} kg	0.390	0.371	0.356	0.347	0.339	0.345	0.352	0.350
10^{-8} kg	0.242	0.241	0.241	0.238	0.241	0.252	0.281	0.294

Meteoroid masses not included in the table had maximum light intensities fainter than $+8^M$.

least 10^{-8} kg last long enough to be present in a number of video frames, so this is not an observing limitation.

High geocentric velocity meteors are characterized by very long trail lengths (see Hill et al., 2005). It is, therefore, possible that although a meteor lasted for several video frames, its high angular velocity might result in less than one full video frame within the field of view (preventing a velocity calculation). The angular displacement traversed in one standard video frame ($\frac{1}{30}$ s) by the modelled meteors detected at their points of peak light intensity in the centre of the field of view of a ground-based observing system pointed directly at zenith is displayed in Figure 3. Even the fastest heaviest meteoroid modelled travels just 2.3° in one video frame. Since most fields of view in use in meteor detection (Hawkes, 2002) are significantly in excess of this, high geocentric velocity meteors should be detected in multiple video frames electro-optically.

The greater angular velocities of high geocentric velocity meteors also have the effect of reducing the apparent meteor magnitudes. The faster meteor will cross proportionally more pixels across the CCD in one integration period and have a corresponding reduction in apparent magnitude. Hawkes

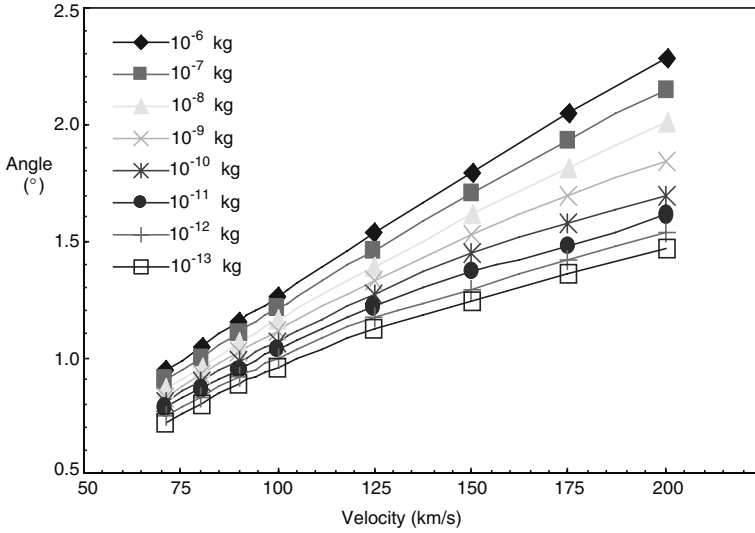


Figure 3. Plot of angle traversed by meteor during one video frame ($\frac{1}{30}$ s), versus the geocentric velocity (in km/s).

(2002) shows that to first order the meteor limited magnitude, m_m , is related to the apparent stellar magnitude of an observing system, m_s , by the following relationship, where d is the number of pixels of effective resolution traversed by the meteor in a single frame integration time.

$$m_m = m_s - 2.5 \log d \quad (1)$$

For example, it can be seen in Figure 3 that for a 10^{-8} kg meteoroid having a zenith angle of 45° detected at its point of peak light intensity, doubling the initial velocity from 100 to 200 km/s results in a 72% increase of the angular velocity of the meteor from 1.16° to 2.00° in one frame ($\frac{1}{30}$ s).

Meteors with very high geocentric velocities also suffer a decrease in detection probability due to observing system geometry. Due to their high ablation heights very high velocity meteors will be biased against in conventional multi-station meteor observations (Woodworth and Hawkes, 1996). This effect is most significant for small fields of view pointed in directions well offset from the vertical.

5. Discussion

We will first consider potential limitations of the model used. This paper has only dealt with cometary structure meteoroids. A later paper (Hill et al., 2005) will consider other structures. An isothermal meteoroid was assumed

which should be valid for the small meteoroid masses employed. Although meteor ablation heights are independent of the luminous efficiency factor, the meteor absolute magnitudes presented here depend strongly on the luminous efficiency assumed. While it has been shown that physical sputtering is a significant ablation mechanism (Hill et al., 2005; Rogers et al., 2005), the model employed considered thermal meteoroid ablation only. Because the importance of sputtering has been shown to diminish at high velocities (Rogers et al., 2005), and because the results presented in this work are dependent on the later portions of the meteor light curve where thermal ablation dominates, sputtering is not expected to play a large role.

The model results suggest that, although they are not as bright as would be anticipated by a linear dependence of the luminous efficiency factor on velocity, very fast meteors having initial (pre-atmospheric) masses of at least 10^{-8} kg would be bright enough to be detectable by typical sensitive electro-optical meteor equipment (see Hawkes (2002) for a review). There are several biases though, which have been described in the Observational Implications section.

The results from our model can assist in optimising a search strategy for high velocity meteoroids. A multi-station observing system configured to an appropriate optimum intersection altitude on the order of 120 km is required. Because very few high velocity particles having masses larger than 10^{-7} kg would be ejected from pre-main sequence stars by radiation pressure (Quirt and Hawkes, 2005), one would need a system capable of detecting very small faint meteors. A moderately large aperture system would be advisable. Unfortunately, this usually implies a relatively narrow field of view which would increase the observational bias. This may be overcome by using several systems at each station directed at slightly different but overlapping fields to create a large net field of view.

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6. Appendix A

6.1. THERMAL ABLATION EQUATIONS AND PARAMETERS

The differential equations describing the motion through the atmosphere of an isothermal, homogeneous, single body meteoroid experiencing thermal

ablation in the free molecular flow regime are presented below. The thermal and physical meteoroid parameters found within the equations are defined in Table A1, and the values employed in the model are provided. More information on thermal ablation theory may be found in Öpik (1958), McKinley (1961), Hawkes and Jones (1975), Ceplecha et al. (1998) and Fisher et al. (2000).

The rate of change of the meteoroids height above the surface of the Earth, h , is related to the meteoroids velocity, v , by simple trigonometry.

$$\frac{dh}{dt} = -v \cos z \quad (\text{A.1})$$

The deceleration of the meteoroid can be obtained through conservation of linear momentum, where m is the meteoroid mass and ρ_a represents the atmospheric mass density.

$$\frac{dv}{dt} = -\frac{\Gamma A}{m^{1/3} \rho_m^{2/3}} \rho_a v^2 \quad (\text{A.2})$$

The rate of change of temperature, T , of an isothermal meteoroid may be derived from conservation of energy.

$$\frac{dT}{dt} = \frac{A}{cm^{1/3} \rho_m^{2/3}} \left(\frac{1}{2} \Lambda \rho_a v^3 - 4\sigma\epsilon(T^4 - T_a^4) + \frac{L}{A} \left(\frac{\rho_m}{m} \right)^{2/3} \frac{dm}{dt} \right) \quad (\text{A.3})$$

We used the vapour pressure relationships given by the Clausius-Clapeyron equation to model the rate of meteoroid mass loss following

TABLE A1
Physical and thermal meteoroid parameters

Symbol	Definition	Numerical Value
z	zenith angle	45°
ρ_m	meteoroid mass density	1000 kg m ⁻³
Γ	drag coefficient	1.0
A	shape factor	1.21
Λ	heat transfer coefficient	1.0
ϵ	emissivity	0.9
T_a	atmospheric temperature	280°
c	specific heat of meteoroid	1200 J K ⁻¹ kg ⁻¹
L	latent heat of fusion plus vaporisation	6.0 × 10 ⁶ J kg ⁻¹
μ	mean molecular mass of ablated material	20 amu
C_A, C_B	Clausius Clapeyron parameters	10.6, 13,500 K

Bronshten (1983) and Adolfsson et al., (1996).

$$\frac{dm}{dt} = -4A \left(\frac{m}{\rho_m} \right)^{2/3} 10^{C_A - \frac{C_B}{T}} \left(\frac{\mu}{2\pi k T} \right)^{1/2} \quad (\text{A.4})$$

The light intensity of the meteor, I , may be related to the rate of mass loss though the luminous efficiency factor, τ_I .

$$I = -\frac{\tau_I}{2} \frac{dm}{dt} v^2 \quad (\text{A.5})$$

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ELEMENTAL ABUNDANCES IN LEONID AND PERSEID METEOROIDS

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Abstract. High dispersion photographic spectra of three Leonid and five Perseid meteors are used to derive relative abundances of nine chemical elements in the radiating meteoric vapors and in the meteoroids. Al and Ca were found to be incompletely evaporated in the main spectral component at 5000 K but completely evaporated in the second component at 10,000 K. Si lines are present in both components which enhances the reliability of determination of the Si abundance. The composition of the meteoroids was found to be more similar to comet Halley than to chondritic meteoroids. Fe, Cr, and Mn are depleted and Si, Na, and H are enhanced relative to Mg in comparison with CI chondrites.

Keywords: Meteors, meteoroids, spectroscopy, composition, comets

1. Introduction

The measurement of composition of cometary meteoroids is of large interest because no meteorites of clearly cometary origin are known and interplanetary dust particles cannot be easily linked to their parent bodies. The *in situ* measurements of the dust of comet Halley gave major element ratios markedly different from chondritic meteorites (Jessberger et al., 1988). A big progress is expected from the sample return of the Stardust probe in 2006. Detailed analysis of the dust of Jupiter family comet Wild 2 will be possible. Here we report spectroscopic measurements of Leonid and Perseid meteors which are products of two Halley-type comets, 55P/Tempel-Tuttle and 109P/Swift-Tuttle, respectively.

2. Description of the Data and their Analysis

Our analysis is based on high dispersion photographic spectra of three Leonid and five Perseid fireballs (Table I). The spectra were taken with large format (18 × 24 cm), *F*/4.5, long focal distance (300 and 360 mm) Tessar cameras equipped with 600 grooves/mm objective transmission gratings and a rotating shutter. The spectra have high resolution, typically 2.5 Å. The very

sharp spectrum S 30132 reached the resolution of $0.8 \text{ \AA}$ in the second order (Figure 1). The corresponding resolving power of our spectra is $\lambda/\Delta\lambda \approx 2000\text{--}5000$. The covered spectral range is $3600\text{--}6800 \text{ \AA}$. The system is sensitive only to very bright meteors. The maximum magnitude of the meteors analyzed here was between -6 and -14 , corresponding to meteoroid masses from 0.01 to 1 kg .

All spectra were digitized using the Microtek Artixscan 2500 flatbed scanner in 2500 dpi resolution and 12 bit intensity scale. All subsequent measurements were done on digital images. Stellar spectra and zero order images were used to obtain the spectral sensitivity and characteristic curve. The meteors were analyzed only at their brightest points. The wavelength scale was fitted to several well recognizable spectral lines.

As usual for fast and bright meteors, lines of two spectral components (Borovička, 1994) are visible in all analyzed spectra. The main component contains a number of Fe I lines and also lines of Mg I, Na I, Ca I, Mn I, Si I, Cr I, and Al I. Only one line or few lines of the same multiplet are usually visible for elements other than Fe. On the other hand, the high resolution enabled us to measure easily the lines of Al I and Si I which are blended with nearby lines of Ca II and Fe I in spectra of lower resolution. Especially the Si I line at $3905 \text{ \AA}$ (Figures 1 and 2) is important because it enabled us to derive Si abundance in both spectral components and enhance the reliability of the abundance measurement of Si. The second, high

TABLE I
The list of spectra

No	Date	Shower	No	Date	Shower
S 25196	1997-08-07	Perseid	S 27554	1999-08-13	Perseid
S 25212	1997-08-12	Perseid	S 27922	1999-11-16	Leonid
S 25221	1997-08-13	Perseid	S 27934	1999-11-18	Leonid
S 25225	1997-08-13	Perseid	S 30132	2001-11-15	Leonid

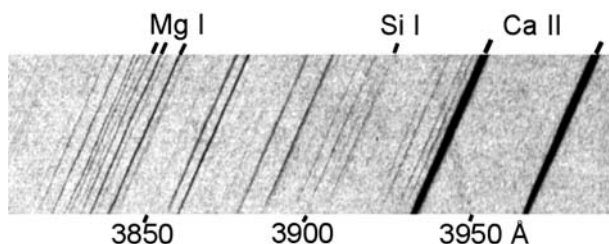


Figure 1. Part of the S 30132 spectrum in the second order. Important lines other than Fe I are identified.

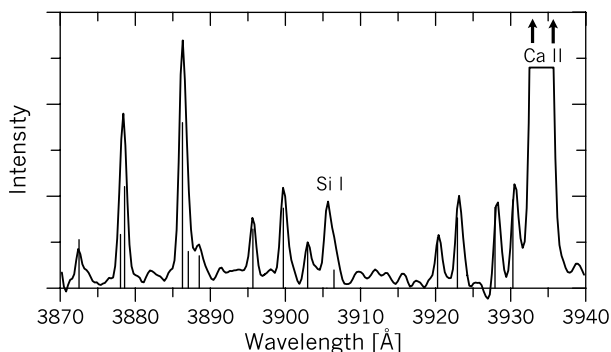


Figure 2. A section of the second order spectrum S 30132 showing clearly the Si I line at 3905.5 Å. The positions and expected intensities of Fe I lines are marked by vertical bars.

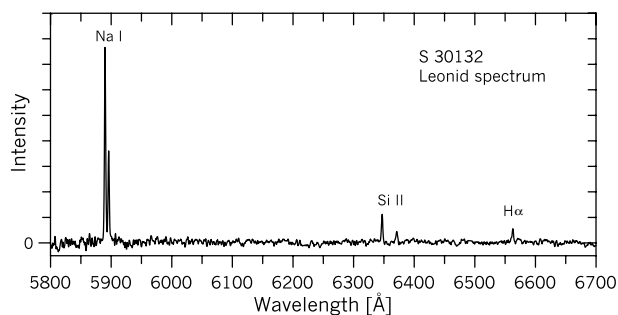


Figure 3. Red part of the first order spectrum S 30132 showing the Na I doublet, Si II doublet and H α line.

temperature, component contains lines of Ca II, Si II, Mg II, Fe II, and H I. Only the Si II lines are more numerous. Hydrogen is represented by the H α line, visible in most spectra (Figure 3).

The line intensities were fitted by the least squared method of Borovička (1993). The method assumes thermal equilibrium in meteor plasma. This assumption was proven to be usable not only by fitting successfully many observed spectra but also theoretically (Boyd, 2000). The lines prominent in meteor afterglows (Borovička and Jenniskens, 2000) had, nevertheless, to be excluded in some cases. The results of the fits are given in Table II. The free parameters are the temperature, T , the column density of a reference atom, N , and relative abundances of other atoms. For the main spectrum, Fe I lines were used to determine the temperature and Fe I is used as the reference atom. For the second spectrum, the temperature could be determined reliably from the Si II lines in one spectrum only (S 27922) and was assumed to be close to 10,500 K for other spectra.

3. Correction for Ionization

To convert the relative abundances of neutral or singly ionized atoms from Table II into elemental abundances, ionization conditions in both spectral components must be evaluated. Knowing the temperature, ionization degree of individual elements can be computed from the Saha equation provided that electron density, n_e , is estimated. In Borovička (1993), I used the known meteor magnitude to evaluate the volume of the radiating gas and the densities of atoms and electrons. Here I take the advantage of having two spectral components. I assume that the abundances of the main elements, Mg, Si, and Fe, are the same in both components and that the electron pressure, p_e , is the same:

$$p_e = n_{e1}kT_1 = n_{e2}kT_2. \quad (1)$$

Here k is Boltzmann constant. The Saha equation was applied to both components assuming various values of n_{e1} and the convergence of the resulting Si/Mg ratio in both components was searched for. The agreement was not perfect in all spectra but the best values of n_{e1} proved to be between 5×10^{13} and $2 \times 10^{14} \text{ cm}^{-3}$.

TABLE II
Fitting parameters of the two spectral components in meteors

	25196	25212	25221	25225	27554	27922	27934	30132
T_1 [K]	5000	5100	5000	4800	5100	5200	4900	5300
$N_{\text{Fe I}}^a$	90	10	60	50	65	40	30	150
Na I $\cdot 10^{-3}$	8	6.5	9	10	7.5	8	3	10
Mg I	2.5	3	3	1.9	3.5	2.2	2.5	2.3
Al I $\cdot 10^{-3}$	4	—	10	—	30	20	20	7
Si I	8	—	7	—	6	8	7	12
Ca I $\cdot 10^{-3}$	0.6	1	1	1.3	2	1.7	0.5	1
Cr I $\cdot 10^{-3}$	2	—	4	—	3	3	3	4
Mn I $\cdot 10^{-3}$	9	—	6	—	6	7	6	10
Fe I	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$
T_2 [K]	10500	10500	10500	10500	10400	10600	10500	10500
$N_{\text{Mg II}}^a$	10	10	10	10	10	50	100	50
H I	2	—	2	4	2.5	0.6	1.2	3
Mg II	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$
Si II	7	4	8	5	5	7.5	5	4
Ca II $\cdot 10^{-3}$	10	10	10	12	3.5	5	6	12
Fe II	—	—	—	—	0.3	0.7	—	0.8

^a in 10^{12} cm^{-2} .

To provide more insight into the problem, typical ionization conditions of observable elements in both components are given in Table III. The bold numbers represent observed species. In both components, Si is least affected by ionization. This is the reason for the high abundances of Si I and Si II (see Table II). On the other hand, Na I and Ca I in the main component and Ca II and H I in the second component represent only a small minority of the respective element. No Na II lines are present, but neglecting the Na ionization as it was done recently by Kasuga et al. (2004) leads to absolutely wrong Na abundances. The Ca II lines can be present in the main component, their intensity in the present spectra is, nevertheless, quite negligible in comparison with the intensity of the same lines in the second component.

Table IV lists the ionization correction factors for different values of electron densities n_{e1} . The ionization correction factor is the number to multiply the observed ratio $El\ i/\text{Mg I}$ (in the main component) or $El\ i/\text{Mg II}$ (in the second component) to obtain the total El/Mg ratio (El is an element). Na, Ca, and Si are the elements most affected by ionization. Na and Si are affected in the opposite way, so the Na/Si ratio is extremely sensitive to ionization correction. The Mn I/Mg I ratio, on the other hand, is almost

TABLE III
Typical ionization conditions in meteor plasmas

	$T = 5000\text{ K}, n_{\text{e}} = 10^{14}\text{ cm}^{-3}$		$T = 10,500\text{ K}, n_{\text{e}} = 4.8 \times 10^{13}\text{ cm}^{-3}$		
	I	II	I	II	III
H			3%	97%	0
Na	1.7%	98.3%			
Mg	60%	40%	0	23%	77%
Al	27%	73%			
Si	94%	6%	0	78%	22%
Ca	4%	96%	0	0.9%	99.1%
Cr	31%	69%			
Mn	61%	39%			
Fe	74%	26%	0	35%	65%

TABLE IV
Ionization correction factors to Mg for different electron densities

n_{e1}	H I	Na I	Al I	Si I	Si II	Ca I	Ca II	Cr I	Mn I	Fe I	Fe II
10^{13}	10	73	3.6	0.21	0.11	31	32	3	0.96	0.58	0.58
10^{14}	8.2	34	2.2	0.64	0.30	15	26	1.9	0.98	0.80	0.66
10^{15}	3.3	6.2	1.2	0.94	0.77	3.2	9	1.1	1.0	0.97	0.89

insensitive to ionization. The ionization factors change only little for $n_{e1} \ll 10^{13} \text{ cm}^{-3}$ and converge to unity for $n_{e1} \gg 10^{15} \text{ cm}^{-3}$.

4. Resulting Abundances

The resulting abundances in the radiating gas of eight meteors are given in Table V. The abundances normalized to Mg are given separately for both spectral components. The abundances in CI chondrites (Anders and Grevesse, 1989; Lodders, 2003) are given for comparison in the last column. The comparison is provided also in the graphical form in Figure 4.

The refractory elements Al and Ca are underabundant in the main component, i.e. at $\sim 5000 \text{ K}$. This can be ascribed to the effect of incomplete evaporation which was noted earlier (Borovička, 1993). Recently, this effect was quantitatively confirmed by thermochemical calculations of Schaefer and Fegley (2004). There is no depletion of Ca in the second component at $\sim 10,000 \text{ K}$.

The evaporation of other elements should be complete or almost complete. We propose that the observed deviations from the CI abundances reflect the real composition of the meteoroids. Cr, Mn, and Fe are severely depleted in both Leonids and Perseids. Si, Na, and H are enhanced, though there is a large scatter of the Na and H values in Leonids. The Fe depletion

TABLE V
Relative elemental abundances in two spectral components of meteors

	25196	25212	25221	25225	27554	27922	27934	30132	CI ^a
Na	0.11	0.10	0.11	0.14	0.10	0.11	0.035	0.18	0.056
Mg	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$
Al ^b	3	—	8	—	20	20	15	7	79
Si	2	—	1.4	—	0.7	2	2	1.9	0.98
Ca ^b	3.5	6.5	5	7	13	12	2.5	9	58
Cr ^b	2	—	2.5	—	2	2.5	2	4	13.5
Mn ^b	3.5	—	2	—	1.7	3	2	4	8.5
Fe	0.3	0.2	0.25	0.45	0.2	0.35	0.35	0.3	0.85
H	16	—	16	30	20	4.5	10	25	11
Mg	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$
Si	2	0.8	2.4	1.4	1.2	3	1.4	1.3	0.98
Ca	0.25	0.25	0.25	0.3	0.10	0.11	0.15	0.3	0.058
Fe	—	—	—	—	0.2	0.5	—	0.55	0.85

^a CI chondrites.

^b multiply by 10^{-3} .

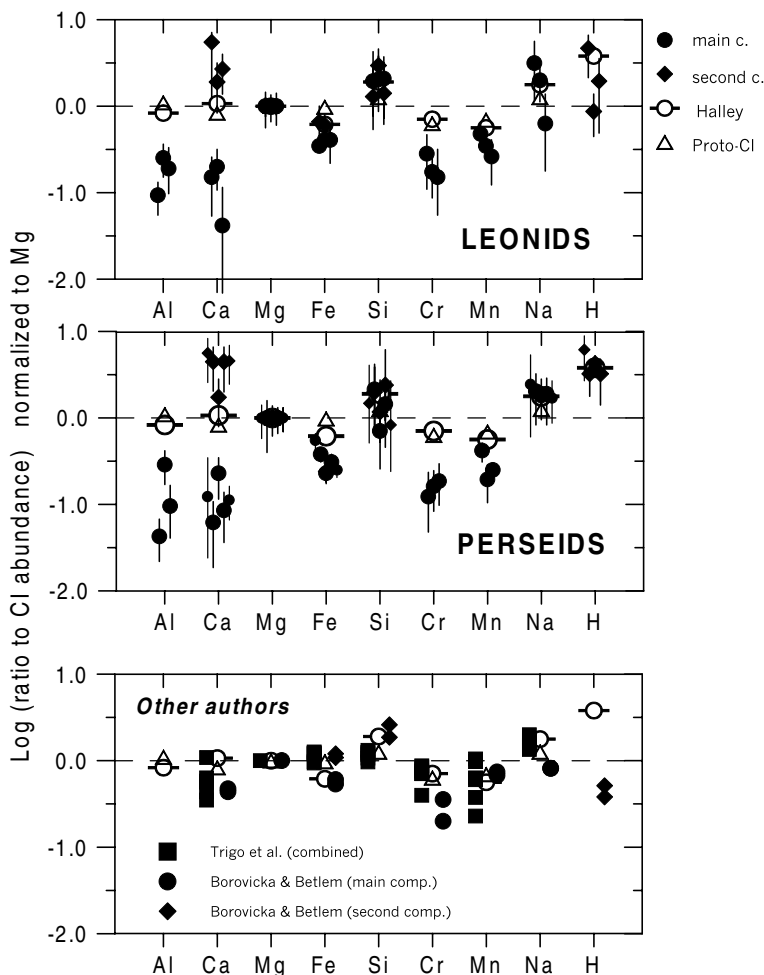


Figure 4. Relative abundances of nine elements in the radiating gas of three Leonid meteors (upper panel) and five Perseids (middle panel, data from poor spectra are plotted as smaller symbols). The abundances are normalized to Mg and displayed on logarithmic scale as deviations from the chondritic CI composition. The two spectral components are treated separately. The errors of individual measurement are plotted as vertical bars. The compositions of Comet Halley dust (Jessberger et al., 1988) and a hypothetical proto-CI material (Rietmeijer and Nuth, 2000) are displayed for comparison. The elements are ordered in the sequence of increasing volatility, from the left to the right. The lower panel contains Perseid and Leonid data taken from the literature.

seems to be higher and the Si enhancement lower in Perseids than in Leonids. In other words, silicates seems to be more Mg-rich in Perseids. Ca, as measured in the second component, seems to be enhanced over the CI value. This result must, however, be taken with caution because it is based on extremely bright Ca II lines (see Figure 1) which are difficult to calibrate.

Table VI contains the mean abundance deviations from the CI composition in Leonid and Perseid meteoroids. The less precise measurement of poorer spectra got smaller weight in computing the mean. The measurements of Al and Ca in the main spectral component were not used.

5. Discussion

The reliability of our results is supported by the fact that the deviations from CI composition show the same pattern as for comet Halley (Jessberger et al., 1988). The comparison is provided in Figure 4 and Table VI. Mg, Si, Na, and H show the same abundances as in Halley or between CI and Halley. Cr and Mn are depleted in Halley and show even larger depletion in Leonids and Perseids. Fe is depleted similarly to Halley in Leonids and more in Perseids. The abundance of Ca seems to be higher than in both CI and Halley. This result is, however, uncertain because it is based on extremely bright Ca II lines. Ca I and Al I lines cannot be, unfortunately, used because of incomplete evaporation of Ca and Al in the low temperature component.

The composition of Leonids and Perseids was discussed several times in the literature. Here we consider only the measurements which used the least squares fit to meteor spectra, namely those of Borovička and Betlem (1997) and Trigo-Rodríguez et al. (2003). They are plotted in the lower panel Figure 4. In general, these old results are closer to CI composition, nevertheless, the depletion of Cr and Mn is evident. Some points also suggest enhancement of Na and Si and depletion of Fe. On the other hand, the Trigo's values show chondritic Si–Mg–Fe ratios. They are, however, based on prism spectra with lower resolution and may be less reliable. None of the older work was able to use the Si I line in the main spectrum.

We conclude that the significant deviation of the composition of the dust from CI chondrites is not unique to Halley's comet nor is it restricted to very small dust particles. The derived dust composition may be representative for

TABLE VI
Weighted mean deviations of meteoroid composition from CI chondrites

Shower	H	Na	Si	Ca	Cr	Mn	Fe
Perseids	+0.62 ±0.12	+0.28 ±0.04	+0.14 ±0.17	+0.58 ±0.19	−0.80 ±0.07	−0.54 ±0.13	−0.53 ±0.12
Leonids	+0.30 ±0.25	+0.27 ±0.23	+0.20 ±0.13	+0.56 ±0.20	−0.71 ±0.11	−0.43 ±0.10	−0.26 ±0.10
Halley	+0.58 ±0.08	+0.25 ±0.20	+0.28 ±0.04	+0.03 ±0.11	−0.15 ±0.09	−0.25 ±0.15	−0.21 ±0.07

In logarithmic scale, normalized to Mg.

the majority of Halley type comets. Our results support the view of Rietmeijer and Nuth (2000) who proposed that cometary dust represents an anhydrous proto-CI material. Nevertheless, variations from comet to comet are obvious as Leonids and Perseids are more severely depleted in Cr and Mn than comet Halley.

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RADIANTS OF THE LEONIDS 1999 AND 2001 OBTAINED BY LLTV SYSTEMS USING AUTOMATIC SOFTWARE TOOLS

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Abstract. Both amateur and professional meteor groups are more frequently using Low-Light level TV (LLTV) systems to record meteors. Double-station observations can yield orbit data. However, data analysis normally is still done by hand and thus time consuming. This paper addresses the question of whether available automated tools can be used to determine reasonably accurate orbits with minimum human intervention. The European Space Agency performed several observing campaigns to observe the Leonid meteor stream. In November 1999, the ESA meteor group was stationed at two locations in Southern Spain, in November 2001 at two stations close to Broome in North-Western Australia. Double-station observations with LLTV systems were conducted. The data was recorded on S-VHS video tapes. The tapes were processed using automatic detection software from which meteor heights, velocities and radiants were computed. This paper shows the results for the two maximum nights. The radiants determined in 1999 show a very large scatter due to unfortunate observing geometry and inaccurate position determination since one of the cameras was moving because of the wind. The 2001 data is excellent and the radiant was determined to be at $RA = 153.96^\circ \pm 0.3^\circ$ and $Dec = 21.09^\circ \pm 0.2^\circ$. The error bars for individual meteor radiants are about 0.2° to 0.4° . This demonstrates that is indeed possible to determine good radiant positions using totally automated tools. Orbits, on the other hand, are not well defined due to the fact that the velocity of individual meteors shows large errors. Reasons for this are described.

Keywords: Meteoroids 2004, meteors, Leonids, radiants, LLTV systems, video observations, predictions, automated video systems

1. Introduction

Traditionally, meteor orbits were determined from photographic observations, both using all-sky cameras or batteries of 35 mm film cameras. In recent years, image-intensified video cameras (Low-Light level TV, LLTV) and automatic detection and analysis software has become available in the professional and amateur community. While a video system lacks the resolution of photographic film, the smaller field of views of the cameras combined with much better sensitivity (visual magnitudes of typically 6–8 mag can be recorded) make video systems attractive for orbit determination.

This paper presents results from double-station video camera setups operated during the 1999 and 2001 Leonid meteor campaigns of the Research and Scientific Support Department (RSSD) of the European Space Agency (ESA). In particular, we were interested in finding out whether a fully automated double-station setup would be feasible. It will be shown that this would indeed be possible.

2. The ESA/RSSD Meteor Cameras

The ESA/RSSD meteor group operates two types of meteor cameras. The “Intensified CCD Camera (ICC)” uses a second generation intensifier type DEP XX1700 with a fiber-coupled CCD detector. The CCD is read out by a commercial Sony XC-77DE video camera which can deliver 12 bits of dynamic range. A second camera type, called Low-Cost Camera (LCC), uses second-generation DEP XC1771 intensifiers. Their output was recorded with single-board video cameras (Conrad) with a relay lens. This camera can be read out with 8 bit dynamical range.

Different lenses can be used on the cameras. They are typically operated with Rayxxar lenses (50 mm f/0.75, 80 mm f/1.0), Fujinon (25 mm f/0.85 C-mount) or Zenith (16 mm f/2.8 M42). The configuration used here is given in Table I.

The camera signal was recorded via S-VHS recorders on video tape, limiting the resulting dynamical range to about 7 bit for both camera systems. Time inserters (Dr. Cuno, Nuremberg) were used to insert the time into the video image. In 1999, the inserters were started at 19h00m00s UT on 17 Nov. In 2001, these time inserters were synchronised with GPS receivers and show the time in UTC (Figure 1).

TABLE I

Observing locations of the ESA/RSSD meteor group for the Leonids 1999 and 2001 and the camera configuration used for this study

	Name	Latitude	Longitude	Altitude	Camera	FoV
1999	Observatory Sierra Nevada (OSN)	03°23'05" W	37°03'51" N	2896 m	ICC3 80 mm f/1.0	5.6°×7.5°
	Calar Alto Observatory (CAHA)	02°32'47" W	37°13'25" N	2168 m	ICC2 50 mm f/0.75	12°×15°
	Lake Eda	17°53'20" S	122°38'52" E	130 m	LCC3 28 mm f/2.8	22°
2001	Dampier	18°22'40" S	123°07'46" E	130 m	ICC2 50 mm f/0.75	12°×15°
	Downs					

N is the number of meteors recorded in the night of the maximum, M the number for which good double-station radiant calculations were obtained.

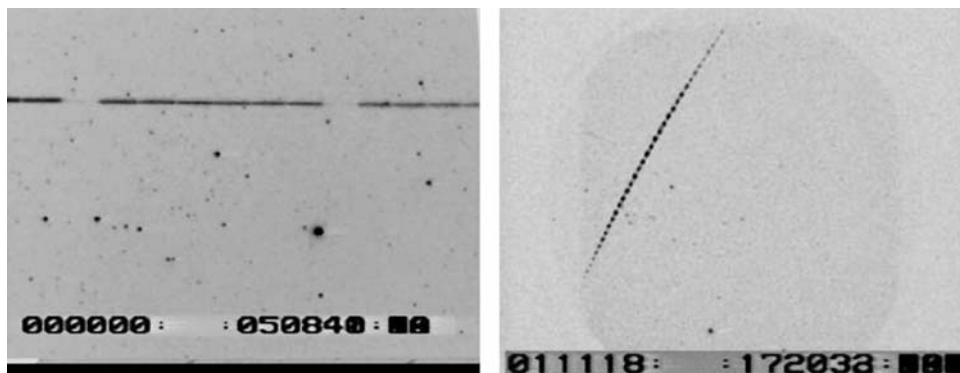


Figure 1. Sample meteor images (negative) obtained with the ESA/RSSD meteor cameras. Left: ICC3, 18 Nov 1999, 00h08m40s UT. The breaks in the meteors path are a result of dropped frames. Right: LCC2, 18 Nov 2001, 17h20m32s UT. Every second frame was recorded.

3. Observing Setup 1999 and 2001

The observing sites for the Leonid campaigns were selected according to visibility constraints and weather predictions. In 1999, the equipment needed support from the local infrastructure, in particular 220 V AC current, whereas in 2001 all equipment was fully portable and could be operated from car batteries. Thus, in 1999 we selected two observatory sites in Southern Spain, namely the Observatory Sierra Nevada (OSN) south of Granada, and the Calar Alto Observatory (CAHA), about 60 km east of OSN. In 2001, we used four-wheel drive cars to reach two sites in the outback around Broome in North-Western Australia, close to Lake Eda and Dampier Downs. Table I gives a summary of the observing locations (from Koschny et al., 2002).

4. Analysis Method

All video data was recorded on (S-)VHS video tape. The video tapes were searched for meteor events using the software MetRec (Molau, 1999). Before the start of the search, one frame is grabbed and read into RefStars (Molau, 1999) for finding out the pointing direction of the camera. This allows MetRec, together with the time of the detected event, to compute the Right Ascension and Declination of the meteor.

MetRec generates a log file listing all meteors and a summary plus one file for each meteor with the position of the event in each video frame the meteor was detected. These files are used by a tool called Meteor Trajectory and Orbit Software (MOTS; Koschny and Diaz del Rio, 2002) to compute each meteor's radiant and, eventually, its orbit. In the paper presented here, we used MOTS to generate radiants only.

MOTS uses the following algorithm. The Right Ascension (R.A.) and Declination (Dec.) for the meteor in each frame as seen from camera 1 are interpreted as vectors, to which a plane is fitted. This plane encompasses the meteor path and the location of camera 1. Each R.A. and Dec. value as seen from camera 2 is again interpreted as a vector. The intersection of this vector with the plane gives a point in x/y/z coordinates in an Earth-centred coordinate system. Doing this for all video frames from camera 2 yields positions of the meteor in space. A straight line fit to these positions gives the path of the meteor. The calculation can be repeated with camera 2 as a starting point. Converting the backward prolongation of the path to R.A. and Dec. gives the coordinates of the meteor's radiant.

Each individual step of the computation is based on all points on the trajectory. E.g. for the radiant, the backward prolongation for each trajectory point pair can be computed. A weighted average is used for the final result, and the error is estimated from the data to allow some quality control station. A detailed description can be found in Koschny and Diaz del Rio (2002).

5. Results

5.1. THE DATA FROM 1999

While the Right Ascension of the radiant positions was within the expected range around 154° , the Declination was varying between 15° and 50° . Clearly, this variation is not real. Careful analysis showed the following:

The observing geometry was very unfavourable. The two observing stations were in east–west orientation, whereas the observing direction was towards the North (directly to the pole star from OSN). For most of the observing time the meteor radiant was low in the eastern sky and the meteors can be envisaged as describing approximately horizontal lines north of the two stations. Now consider the description of the algorithm as given in the previous section. The plane formed by station 1 and the meteor and any viewing direction from station 2 to the meteor fall almost together. Small errors in angle thus convert into large shifts in position in space, resulting in a large error of the radiant.

5.2. THE DATA FROM 2001

In 2001 the observing geometry was chosen to be more favourable. The intersection angle between the two stations and the meteors was approximately 90° and good results were obtained.

Figure 2 shows the obtained geocentric radiants, corrected for zenithal attraction and diurnal aberration. MOTS estimates errors in Right Ascension

(R.A.) and Declination (δ) from its computations, these are shown for each individual radiant and are typically $\pm 0.3^\circ$ for R.A. and 0.1° for δ . The average value is $153.96^\circ \pm 0.3^\circ$ and $\delta = 21.09^\circ \pm 0.2^\circ$, shown as a thick cross in the Figure. Note that all radiants were corrected for radiant drift by shifting them to a radiant time of 20h00m UTC on 18 Nov 2001.

The Figure also shows the predicted value by McNaught and Asher (2001). All values are summarised in Table II.

6. Discussion

6.1. SOFTWARE PERFORMANCE

To assess the performance of MOTS, the data from 2001 is followed through the processing in more detail in this section. MetRec detected a total of 110 meteors and 145 meteors in the data obtained with ICC2 and LCC3, respectively. MOTS searched for meteors appearing within a maximum of 4 s time difference and marked 64 meteors as potential parallel observations.

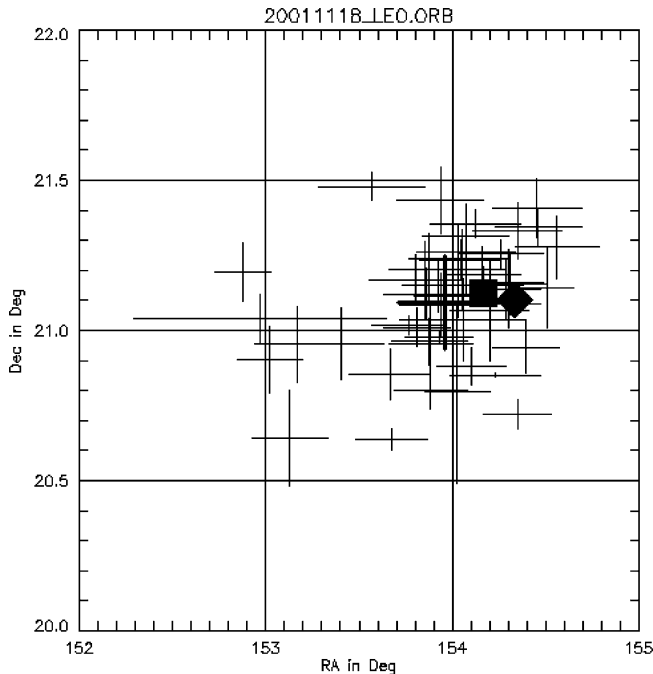


Figure 2. Geocentric radiant positions determined from 48 video meteor pairs. The calculated radiants were corrected for radiant drift to a time of 20h00m on 18 Nov 2001. The thick cross is the mean value. The black diamond and the square denote the predicted radiant for the 4 revolutions trail and 9 revolutions trail, respectively.

TABLE II

Leonid 2001 radiant as determined in this work and predicted values by McNaught and Asher (2001)

	R.A. in deg	Declination in deg
2001 campaign (Australia)	153.96 ± 0.3	21.09 ± 0.2
Prediction:		
9-rev trail (Siding Spring)	154.17	+ 21.12
4-rev trail (Siding Spring)	154.34	+ 21.10

This means that only about 50% of the events occurred in the common field of view, all other meteors were either too far or too close in one camera's field of view. Another possibility is that in one of the cameras the meteor was too faint to be recorded.

Using the 64 potential meteor pairs, MOTS computed altitudes. The acceptable height range was set to 40–180 km. Three pairs did not fall into this range and were rejected. 61 pairs yielded good solutions.

In a few occasions, one meteor from one camera would pair with two meteors seen by the other camera appearing within the accepted time window of 4 s. Obviously only one of the pairs can be the correct one. Here, some manual work was required to analyse the errors and select the proper pair. Note that the chances for this to occur under non-storm circumstances are minimal, as normally meteors don't appear within seconds.

After minimal manual intervention, 57 meteors with good radiant were left. 48 of these were Leonids and their computed radiant are shown in Figure 2.

6.2. RADIANT DETERMINATION

Figure 2 shows that the radiant predicted by McNaught and Asher (2001) are well within the observed radiant, i.e. the prediction fits well. There is a scatter around the predicted radiant which is similar to the orbit cross-section plots given by McNaught and Asher. The scatter in the individual radiant is much larger than the difference between the 4 revolution trail and the 9 revolution trail, so the trails cannot be distinguished via the radiant. As the error bars from the processing are only a little smaller than the scatter of individual radiant, it cannot be ruled out that processing errors smear out the individual trail directions.

Torii et al. (2003), Shigeno et al. (2003), and Ueda et al. (2004), find slightly different radiant. However, comparing their data with predictions by McNaught and Asher it can be seen that the difference is the different location of these teams. The authors were located in Japan, where the geo-

centric radiant also was predicted slightly higher than in Australia, see Table III.

Torii et al. (2003) give error bars of about 0.15° , comparable to those obtained by our cameras. Ueda et al. (2004) give error bars which are almost one order of magnitude larger. Thus our setup is clearly comparable to the CCD/telephoto camera system analysed manually.

Spurny et al. (2001) give error bars for radiant determinations of fireballs by the Czech photographic fireball network. They are in the order of $\pm 0.02^\circ$ or better, thus they are again one order of magnitude better than video observations and would – had they the light sensitivity as video systems – allow to separate radiants of different revolutions.

7. Lessons Learnt and Possible Improvements of the Accuracy

In a previous section we already addressed the issue of observing geometry. When setting up double-station systems during the observing campaign of a shower, one should invest some thought into the proper observing geometry. Obviously, for a permanent setup this would play a smaller role as no preferred meteoroid flight direction will be there.

Some of our 1999 data was hard to analyse as we moved the camera's field of view during the night. This should be avoided, as it requires a re-registration of the stars with RefStars.

The main issue with the data from 1999 was that the cameras were not mounted stable enough to withstand the wind (with gusts up to 70 km/h). If observing in strong winds, stable mounting has to be ensured.

One disadvantage of MetRec is that it currently only supports half of the video resolution. It only analyses and stores 384×288 pixels in PAL mode and only even fields, i.e. only 25 fields per second. The full PAL resolution would yield two fields of 388×576 pixels every $1/25$ s, alternating between odd and even lines. This means that effectively only $1/4$ of the possible res-

TABLE III
Radiant positions of the 2001 Leonids as observed from Japan

	R.A. in deg	Dec in deg	Remarks
Torii et al. (2003)	154.35 ± 0.15	21.55 ± 0.15	CCD with telephoto
Ueda et al. (2004)	154.2 ± 1.01	21.5 ± 0.65	Watec CCD, $56^\circ \times 43^\circ$ field of view
	154.4 ± 1.15	21.4 ± 0.42	LLTV system, 17° field of view
Prediction:			
McNaught / Asher	154.18	21.65	9-rev trail (Tokyo)
	154.33	21.60	4-rev trail (Tokyo)

olution is used. Assuming that the errors scale linearly with resolution, error bars as small as $\pm 0.05^\circ$ should be achievable with video systems with the field of views as used here. We have developed a software tool that reads the log file from MetRec and allows to play the video again, then stores full-resolution images. These however currently need to be analyzed manually.

A main problem with the resulting data is that the meteor velocities determined using video data have very large errors. One of the reasons for this seems to be the problem of determining the centroid of an elongated object, as the meteor appears stretched in the possible presence of a wake. This will result in along-path errors in the position of the meteor.

8. Conclusion

We showed that with an observational setup carefully planned, meteor radiants can be obtained with good accuracy using an automated system requiring minimum human interaction. With updates to existing software tools it should be possible to get accuracies which are not more than a factor four worse than photographic radiants, with the advantage of the high light sensitivity of video cameras.

An open issue is the large velocity errors found in video meteor determinations, which will introduce errors in some of the orbital elements.

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VIDEO AND PHOTOGRAPHIC SPECTROSCOPY OF 1998 AND 2001 LEONID PERSISTENT TRAINS FROM 300 TO 930 nm

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Abstract. Spectra of persistent meteor trains were observed at wavelength between 300 and 930 nm. Two obtained train spectra during the 1998 and 2001 Leonid meteor showers are reported here. During the 1998 Leonids, one train was detected by a photographic camera with a spectrograph covering 370–640 nm region. On the other hand, during the 2001 Leonids, video observations were carried out using image intensified cameras in ultraviolet (UV), visible and near infrared (near-IR) wavelengths. Temperatures in persistent trains have been measured by atmospheric O₂ A(0,1) band at the wavelength near 864.5 nm. From a video spectrum obtained just 7 s after parent fireball's flare, a rotational temperature of 250 K at altitude of 88.0 ± 0.5 km was estimated. We can say that the cooling time scale of train strongly depends on the initial mass of its fireball at least for Leonids. Based on cooling constant calculated from our results, we estimated a temperature of ~130 K as a final exothermic temperature at early stage of persistent trains.

Keywords: Airglow, Leonid meteor shower, meteors, persistent train, astrobiology

1. Introduction

Bright fireballs sometimes leave a long-lasting glow that is called a persistent train which lasts long after the disappearance of its parent meteor. It is evident that short lasting trains called a short duration train, which last several seconds at the most, emit a forbidden line of [O I] at 557.7 nm (Halliday, 1958; Millman, 1962) known as the aurora green line. After a rapid decay in intensity, it is generally believed that the luminosity of persistent trains is fueled by reactions involving O₃ and atomic O, efficiently catalyzed by metals from the freshly ablated meteoroids.

Von Konkoly was the first man who carried out a spectroscopic observation of a persistent train by a direct vision spectroscope in 1873 (Herschel, 1881). Afterwards, low resolution photographic spectra of persistent trains were obtained, i.e., six spectra at Banská Bystrica Observatory, Slovakia, observed in 1986–1993 (Rajchl and Peresty, 1992), four spectra in Japan during the 1993 Perseid maximum (Rajchl et al., 1995) and two spectra of the 1993 Perseids in Slovakia (Borovička et al., 1996). All these spectra have shown two main emissions; multiplets of MgI at 518 nm and NaI at 589 nm. The Leonid meteors tend to leave long-lasting persistent trains because of its high entry velocity, ~71 km/s. The parent comet, 55P/Tempel-Tuttle, has an orbital period of 33 years, passed perihelion on February 28, 1998. Therefore, after 1998, the Leonid meteor showers brought us epoch-making observations for persistent trains year by year (Borovička and Jenniskens, 2000; Chu et al., 2000; Jenniskens et al., 2000b; Kelley et al., 2000; Drummond et al., 2001., Abe et al., 2003; Suzuki, 2003). Although the persistent trains has been an object of study for a long time, the physical process of trains is still far from satisfactory. The main reason is that the number of spectrum of persistent train is still lacking and spectrum in the wide wavelength ranges are also still absent. Moreover, spectrum of the persistent trains were obtained only by means of slitless spectrographs which cannot identify molecular emissions precisely. Plane (2003) provides a summary of atmospheric chemistry of meteoric metals.

This paper is intended as an investigation of an early stage of persistent train based on photographic and video spectroscopy with slitless spectrographs in the extensive range between 300 and 930 nm.

2. Observations

We report here slitless spectroscopic observations of persistent meteor trains performed with a photographic camera during the 1998 Leonids and two

image intensified video cameras during the 2001 Leonids. Figure 1 shows sensitivity curves combined with three different spectroscopic instruments. The coverage wavelength was between 300 and 930 nm. The data shown here is based on the analysis of two excellent persistent trains. The first (TR98) and second (TR01) spectrum were obtained in 1998 and 2001, respectively. For photographic results (TR98), we have precise orbital data of the parent meteor and the estimated error of altitude is within ± 0.2 km. While for video results (TR01), orbital information on the parent meteor didn't exist, thus we performed by using several train images observed from different places. Finally, the estimated error of altitude is about ± 0.5 km which depends on the total number of triangulation images. In the following, we defined the time ' $t=0$ ' as the brightest moment of meteor flare and the time precisions are ± 0.5 s for photographic spectra (TR98) and ± 0.03 s for video spectra (TR01).

2.1. PHOTOGRAPHIC OBSERVATION OF THE 1998 LEONID METEOR TRAIN

The photographic observations were carried out using a 35 mm size photographic camera with a grating of 300 grooves/mm, blazed wavelength of 490 nm. The camera was used with an $f=85$ mm, F/1.2 lens and a panchromatic film Kodak T-MAX-400. The observational site was about 20 km east of Nobeyama Radio Observatory of National Astronomical Observatory of Japan ($138^{\circ}.47$ E, $+36^{\circ}.03$ N, 1150 m). The effective spectral region

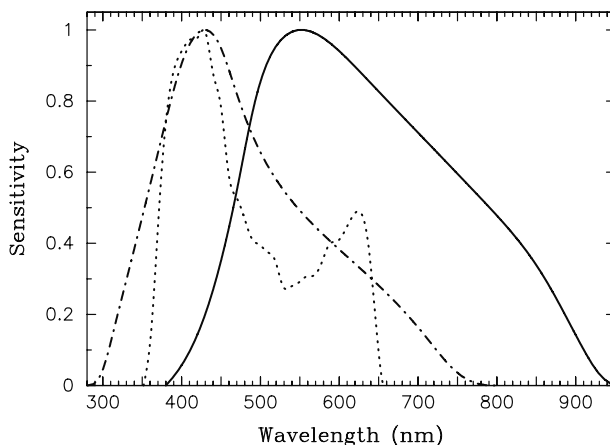


Figure 1. Combined with effective spectral sensitivity responses of three distinguished instruments. The sensitivities were constructed by measuring spectra of bright stars mainly in the observing field and were normalized at its maximum. These sensitivity covered the wavelength at 370–640 nm for photographic (dotted curve), 400–930 nm for the ICCD (thick curve) and 300–750 nm for the UV-II-HDTV (broken curve).

was the wavelength of 370–640 nm. In order to prevent blending of the 1st and the 2nd order image, we used a filter (Kenko L37) which cut off sharply below 350 nm and transmissibility of 50% at 370 nm. One Leonid fireball of which estimated magnitude was -8 appeared at 19:13:55 UT on November 17, 1998. This meteor left a persistent train which was visible by the naked eye for more than 15 min. A 10 s exposure was started from 12 s after the fireball disappearance.

The photographs were digitized with 1024 intensity levels. Dark frame subtracting and flat-fielding were applied to the digital images. A deconvolution method by using a spread function of the persistent train was applied to derive an undisturbed spectrum under an ideal condition because the image showed spreadable distribution caused by the strong upper atmospheric wind within rather long exposure time of 10 s. The spectroscopic image of the persistent train is shown in Figure 2. An analyzed train spectrum with identifications at the altitude of 87.0 ± 0.2 km is shown in Figure 3.

2.2. VIDEO OBSERVATION OF THE 2001 LEONID METEOR TRAIN

Here we report wonderful persistent spectra related with a Leonid meteor fireball, which were observed from two stations at 16:47:24 UT on November 18, 2001. A strong meteor storm activity was well observed around 18:16 UT with the zenithal hourly rate of 3730 caused by a dust trail ejected from comet 55P/Tempel-Tuttle in 1866 McNaught and Asher (1999). Because the physical environment including temperature and density should have changed with time, it would be better to take shorter exposure time. From two stations, spectra were recorded in NTSC video rate, 30 frames per second, and from both stations, the train spectra were obtained just 7 s after meteor flare, the brightest part of the parent fireball which was approximately -8 magnitude.

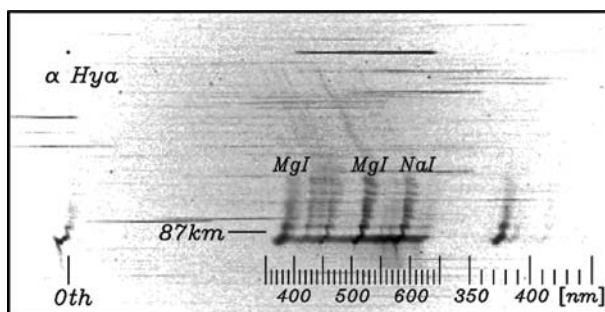


Figure 2. Photographic spectrum of TR98 with an exposure time of 10 s. The dispersion direction is from left to right and the fireball moved from top to bottom. The 0th, the 1st and a part of the 2nd order images were observed.

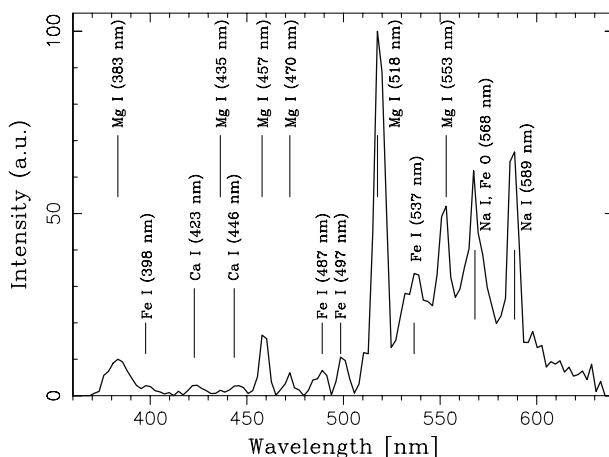


Figure 3. Spectral identifications of TR98 at the height of 87.0 ± 0.2 km, $t = 12\text{--}22$ s. The intensity calibrated by sensitivity response is normalized to 100 at MgI (518 nm). Iron lines are indicated on the extreme down without the atomic name.

2.2.1. ICCD: visible and near-infrared region (400–930 nm)

The observation was done in Tochigi prefecture ($140^{\circ}.05$ E, $37^{\circ}.09$ N, 580 m). The ICCD system consisted of a 150 grooves/mm objective gratings, blazed at 575 nm and a second generation image intensifier (Hamamatsu Photonics, $\phi 28$ mm Night Viewer C3100) which was performed with an $f = 85$ mm, F/1.2 lens. This system provided a circular field of view of 26° in diameter. The spectrum was recorded by NTSC standard digital video camera (SONY PC-3). For taking morphology of persistent trains, the same ICCD system without spectrographs was used on the same observational mount simultaneously. The observing mount had three axes, azimuth, elevation and radiant axes. Once the radiant axis was set to the direction of a radiant of meteor shower, the spectroscopic dispersion direction in the field of view always turned on perpendicular to the meteor path automatically. This special mount takes advantage of unexpected phenomena such as persistent trains because the faster pointing is better and more important for train's spectroscopy. All analyzed spectrum were obtained by averaging of 30 video frames (duration of 1 s) to reduce the noise of the image intensifier. An example of spectroscopic image of the persistent train is shown in Figure 4.

2.2.2. UV-II-HDTV: ultraviolet and visible region (300–600 nm)

Ozone in the stratosphere strongly absorbs below 290 nm, preventing the UV light from reaching the Earth's surface. In order to prevent air extinction owing to mainly aerosol scattering in the UV wavelength below 380 nm, the

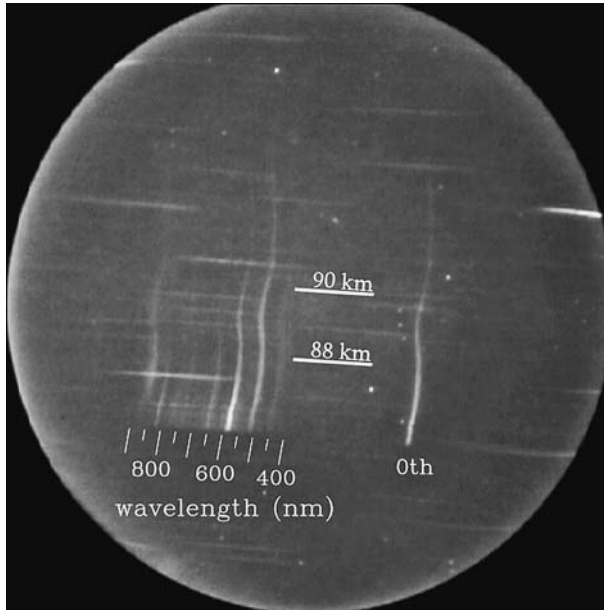


Figure 4. Video spectrum of TR01 by averaging of 1 s (30 frames) before flat-fielding and subtracting of dark and bias. The dispersion direction is from right to left and the fireball moved from top to bottom.

spectroscopic observation was performed at a high-altitude site in the Nobeyama Radio Observatory of National Astronomical Observatory of Japan. The video observations were carried out using an Image-Intensified High Definition TV (II-HDTV) camera in the ultraviolet, visible and near-infrared wavelength regions (250–700 nm). The UV-II-HDTV system consisted of an original uv lens ($f=30$ mm, $F/1.2$), a UV image intensifier (ϕ 18 mm photocathode: S20), two relay lenses ($f=50$ mm, $F/1.4$), and an HDTV camera with and objective spectrometer of a 2 mega pixels CCD. Spectroscopic observations were performed by the UV-II-HDTV system equipped with an objective spectrometer of a reflection grating, which is 600 grooves/mm, blazed at 330 nm, manufactured by the Richardson Grating Laboratory. The rectangular field of view was $23^\circ \times 13^\circ$ in diameter and spectral resolution $\text{FWHM}=2.5$ nm in the first order. Since no order-sorting filter was used, it turns out that the first-order spectrum was mixed with the second-order spectrum in the wavelength longer than 600 nm. The first results of the II-HDTV spectrum obtained from 1999 Leonids and the first results of the UV-II-HDTV spectrum were described in Abe et al. (2000), Abe et al. (2000), and Abe et al. (2005).

From these simultaneous observation in UV and visible region (300–930 nm), an extensive combined spectrum is shown in Figure 5. The identifications of significant compositions are summarized in Table I.

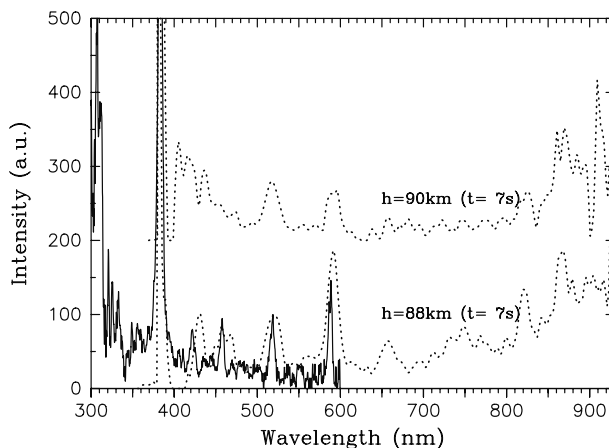


Figure 5. 300–900 nm combined spectrum of TR01 at the height of 88 ± 0.5 km and 90 ± 0.5 km (shifted to upper by 200), $t = 7 - 8$ s. Train spectra were observed by the ICCD (400–930 nm: dotted curve) and the UV-II-HDTV (300–600 nm: thick curve) simultaneously. The intensities calibrated by sensitivity responses are normalized to 100 at MgI (518 nm).

2.3. TRIANGULATION OBSERVATIONS OF PERSISTENT TRAINS

The MEteor TRain Observation (METRO) campaign was widely announced to amateur observers in Japan since the 1998 Leonids and resulted in great success for triangulation observations (Toda et al., 2004; Higa et al., 2005). During the 1998–2001 Leonids over Japan, 173 persistent trains including 53 triangulations were reported with the aid of photographs and video recordings. All these efforts made it clear that the probability of appearance of persistent train was approximately 20% for all Leonid fireballs brighter than -2 magnitude and long-lived trains tended to remain at the altitude between 85.8 and 98.5 km (Yamamoto et al., 2005). The triangulation data provided from METRO campaign enabled us to calculate three-dimensional structure of trains with its precise height information.

3. Results and Discussion

According to the analysis of 8 cases of persistent trains related with Leonid meteoroids, we recognized that continuum dominated emission, so called the molecular phase, begins between 30 and 40 s after meteor disappearance. In the following, we shall focus on an early stage of persistent trains, named the atomic phase, for understanding its physical conditions, that will lead to understand the molecular phase in the future work.

TABLE I
Identifications of Train Spectra of TR98 and TR01. Intensities are normalized to 100 at MgI (518 nm)

λ_{obs} nm	Int. a.u.	λ_{lab}	composition	λ_{obs}	Int. a.u.	λ_{lab}	composition
307.4	554	307.0	OH(A–X)	457.6	95	457.1	MgI
		307.5	FeI	469.8	39	470.3	MgI
309.6	365	309.0	OH(A–X)	478.8	37	478.3	MnI
		309.3	MgI	487.0	32	487.1	FeI
		309.7	MgI	496.4	39	496.6	FeI
310.6	387	310.7	OH(A–X)	516.2	74	515.3	NaI
312.0	385	311.9	FeI	518.8	100	516.7	MgI
320.8	188	320.2	MgI			517.3	MgI
325.8	144	325.8	FeI			518.4	MgI
333.0	131	333.2	MgI	537.4	33	537.1	FeI
		333.7	MgI	553.4	32	552.8	MgI
343.8	51	343.7	NiI	566.6	33		FeO
		344.1	FeI	569.4	33	568.3	NaI
348.8	89	349.1	FeI	586.4	117		FeO
355.8	88	355.9	FeI	588.6	146	589.0	NaI
359.6	80	359.3	CrI	612.3	36	612.2	CaI
		359.8	NiI	620.7	32	620.1	CaI
363.2	66	363.1	FeI	631.2	30	631.9	MgI
368.4	84	368.3	FeI	656.4	65	657.3	CaI
369.6	84	369.5	FeI	673.2	36	672.2	SiI
375.6	146	375.8	FeI			674.2	SiI
382.8	906	382.9	MgI	694.2	36	693.9	KI
		383.2	MgI	713.1	49	714.8	CaI
		383.8	MgI	732.0	70	732.6	CaI
390.0	104	390.0	FeI	746.7	84	746.8	NI
393.2	76	393.0	FeI	767.7	72	766.5	KI
		393.4	CaI	776.1	61	777	OI
397.6	57	397.8	FeI	788.7	55	788.2	MgI
404.6	51	404.6	FeI	799.2	69	797.6	SiI
406.2	53	406.4	FeI			802.7	SiI
410.6	54	410.3	SiI	820.2	134	818.3	NaI
		410.7	FeI			819.5	NaI
421.8	80	421.6	FeI	843.3	95	844.6	OI
422.8	72	422.7	CaI	853.8	100	855.7	SiI
425.0	56	425.1	FeI	862.6	175	863	O ₂
434.8	43	434.5	CrI	866.4	187	866	O ₂
		435.2	CrI	879.0	149	880.7	MgI
		435.2	MgI	895.8	150	894.9	SiI

TABLE I (Continued)

λ_{obs} nm	Int. a.u.	λ_{lab}	composition	λ_{obs}	Int. a.u.	λ_{lab}	composition
443.2	44	443.1	FeI	904.2	153	902.2	SiI
		443.5	CaI	916.8	147	915.4	NaI
446.0	47	445.5	CaI				
		445.9	FeI				
		446.2	FeI				

To begin with, let us consider the emission energy contribution in the persistent train from UV to near-IR wavelength region. Since the UV-II-HDTV spectrum of TR01 was almost comparable to the ICCD spectrum of the same train in the overlapped region between 400 and 600 nm, the intensity ratios were derived from a combined spectrum which was generated by UV–visible and visible–near-IR spectrum after normalization at MgI (518 nm). Ratios of $(300\text{--}400\text{ nm})/(400\text{--}600\text{ nm})=2.5$ from the UV-II-HDTV spectrum and $(300\text{--}600\text{ nm})/(600\text{--}900\text{ nm})=1.0$ from both UV-II-HDTV and ICCD spectra were estimated. It is also important to note that at the lower altitude, 88.0 ± 0.5 km, of the train, NaI (589 nm) was stronger than MgI (518 nm) and was almost comparable to $\text{O}_2(0,1)$ (~865 nm) (Figure 5: lower dotted curve), on the contrary, MgI and $\text{O}_2(0,1)$ were stronger than NaI in the upper altitude, 90.0 ± 0.5 km (Figure 5: upper dotted curve). In addition to this, there are remarkable differences in the spectra shown in Figures 3 and 5, in particular for the ratio of intensities of MgI at 518–383 nm, and existence and non-existence of continuum emission in 530–630 nm. These differences resulted from, (i)time-lag of beginning of exposure after the meteor disappearance, 7 s for TR01 in Figure 5 and 12 s for TR98 in Figure 3, and then the intensity of MgI (383 nm) showed much more stronger than that of MgI (518 nm) at the earlier stage, (ii)exposure time, 1 s for TR01 in Figure 5 and 10 s for TR98 in Figure 3, and then both the atomic and the molecular phase were included in TR98 (Figure 3).

Assuming that the atomic phase persistent train is in local thermodynamic equilibrium (LTE), an excitation temperature of ~2000 K was estimated from our results. However, The train temperature was expected to be lower than 1000 K. Because the density in the train was so low that thermal collisions which were required for LTE should be insufficient, we have to deal with non-equilibrium state. Borovička and Koten (2003) proposed that atomic recombination followed by electron downward cascade was responsible for the population of high levels and this process was a likely mechanism to produce the atomic phase of the train. In this case, the LTE temperature is not appropriate. It is worth while to notice that the equilibrium state of a molecular oxygen band ($b^1\Sigma_g^+$) $\longrightarrow$ ($X^3\Sigma_g^-$) takes advantage of dealing with

physical conditions in persistent trains while atomic lines are under non-equilibrium conditions.

Baggaley (1976) strongly suggested that characteristics of the red train was responsible for an excited atmospheric molecular oxygen, $O_2 A(0,1)$ ($b^1\Sigma_g^+$ state) (hereafter $O_2(0,1)$) first identified in the nightglow by meinel (1950). The presence of the molecular oxygen in a persistent train was first suspected by Hapgood (1980). He reported the enhancement of near-IR emission with the aid of an image isocon television camera which sensitivity covered at 700–900 nm. Long afterwards, Clemesha et al. (2001) also detected $O_2(0,1)$ by means of CCD imaging with a 12 nm bandpass filter. Finally, Suzuki (2003) first identified $O_2(0,1)$ band from several persistent trains which was carried out by a high resolution CCD spectroscopy with 5 s exposure time. Because another vibrational band of $O_2(0,0)$ at 761.9 nm is absorbed by the lower lying atmospheric O_2 and consequently not observed from the ground, (0,1) is the strongest O_2 atmospheric band with the emission origin at 864.5 nm and *P* and *R* branches having maxima around 866 and 863 nm, respectively, that center wavelength slightly depends on excited temperature. Although spectral resolution in our video observation was low, ~ 2 nm, *P* and *R* branches were confirmed separately. The $O_2(0,1)$ showed its strongest intensity at the altitude of 88.0 and lasted until ~ 14 s after meteor flare. Figure 6 indicates comparison between synthetic spectra of $O_2(0,1)$ at appropriate rotational temperatures (100–300 K) and observed spectra. The temperature dependency of the band structure can be seen clearly in the observed train spectra. The train spectra at the altitude of 88.0 km obtained just 7 s after flare is almost in complete agreement with the model spectrum calculated by the rotational temperature of 250 K. Some other (un-identified)

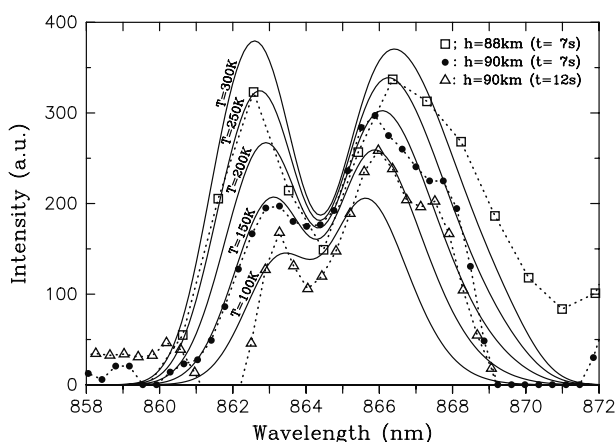


Figure 6. Comparison between synthetic spectra of $O_2 A(0,1)$ at appropriate rotational temperatures (100–300 K) and observed spectra at the altitude of 88.0 and 90.0 km. The intensities of *P* and *R* branches of O_2 emission vary with the rotational temperature.

emission lines may be blended with the pure O_2 (0,1) band beyond 866 nm, or the longer wavelength near the edge of the sensitivity caused a little calibration error. The temperature at the altitude of 90.0 km shows about 150–200 K, which is slightly lower than that of 88.0 km. A temperature of the observed spectrum just 12 s after flare at the altitude of 88.0 km was ~ 150 K. A standard atmospheric temperature at 90.0 km altitude represented by the U.S. Standard Atmosphere (USSA 1976) is 187 K. Chu et al. (2000) reported from lidar observations of a double-tube-structured persistent train that approximately 3 min after ablation, Na temperatures of about 230 K at 92.2 km altitude and 260 K at 92.35 km altitude are compared with our results of O_2 (0,1) rotational temperature of 250 K, even though the time passage was different. Temperature decay curves up to 2 s were reported from -3 to -13 fireball (Jenniskens and Mandell, 2004a). Our results occurred from -8 magnitude fireball can be explained between these two decay curves extrapolated to 7 and 12 s. It seems reasonable to suppose that the cooling time scale of a train depends on the initial mass of its fireball.

During the *afterglow phase*, Borovička and Jenniskens (2000) found that the decay of line intensities depends on excitation potential, not on transition probability. The decay is therefore due primarily to the decrease of temperature, not density. The next equation was found: $5040/T(t) = 5040/T(0) - Dt$. In the case of the *afterglow phase*, the temperature decreased from $T(0) = 4500$ K, typical temperature of Leonid meteors, to $T(2.7) = 1000$ K within 2.7 s and the value of the cooling constant D was found to be $D \sim -1.5$. We adopted this equation to the case of the *atomic phase* of TR01 spectra at $t = 7$ s ($T(7) = 250$ K) and 12 s ($T(12) = 150$ K), respectively. Finally, the same $D \sim -2.7$ was measured from both spectra at $t = 7$ and 12 s. It therefore seems that the above equation is valid for times up to 12 s. The cooling was quicker in this train than in that studied by Borovička and Jenniskens (2000), which was caused by a brighter fireball. The O_2 emission faded away after 14 s in our spectrum. Though P and R branches were not seen clearly due to faint signal at $t = 14$ s, we speculate that after O_2 temperature decreased to ~ 130 K ($t = 14$ s), the exothermic emission was probably declining sharply and the O_2 emission must have disappeared.

Identified emissions in UV, visible, and near-IR ranges in the trains are completely different from Leonid fireballs observed by Abe et al. (2000), Abe et al. (2005), and Trigo-Rodriguez et al. (2004). Of particular interest is the identification of molecular OH emitted in UV region around 310 nm. By means of the same instrument, the same OH feature was identified in a Leonid fireball spectrum (Abe et al. 2005). Further explanations of this emissions must be investigated. Meteors represent a unique chemical pathway towards prebiotic compounds on the early Earth (Jenniskens et al. 2000a, Jenniskens and Mandell 2004b). Because meteor persistent trains could emit in quite low temperature, less than 250 K, a significant fraction of

organic matter is expected to survive after fragmentation from a meteoroid. A long-lasting meteor train will provide us with good opportunities to investigate prebiotic molecules in the future work.

In this paper, we have been focused on *the atomic phase* of persistent trains especially for its emitters in multiple wavelength and induced temperatures resulted from $O_2(0,1)$. On the basis of these results, we are now ready to consider the long-lasting mechanism of *the molecular phase*. However, much still remains to be done in the forthcoming paper.

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ALTITUDINAL DISTRIBUTION OF 20 PERSISTENT METEOR TRAINS: ESTIMATES DERIVED FROM METRO CAMPAIGN ARCHIVES

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Abstract. Observations of persistent meteor trains are limited because of the extreme rarity of the phenomenon. The altitudinal distribution of persistent trains has previously been investigated via limited instances of simultaneous observation from multiple sites, however, a statistical study of persistent trains has yet to be realized. The meteor train observation (METRO) campaign was established in Japan in 1998 to obtain images of persistent trains. From 1998 to 2002, the METRO campaign, involving Japanese amateur collaborators, captured more than 400 image sequences of persistent trains, resulting in 53 simultaneous multi-site observations. Several Japanese observers were involved in imaging persistent trains prior to the METRO campaign, producing 6 simultaneous observations over the period 1988–1997. In this paper, simultaneous multi-site observations of high spatial and temporal resolution are used to determine, via triangulation, the altitudinal distribution of persistent trains for 20 events. The altitudinal range of 2 Orionid trains was slightly higher than that of 18 Leonid trains. The Leonid train data reveal no clear dependence of upper and lower altitude on the brightness of the associated fireball. The upper altitude of the 18 observed Leonid trains were almost invariant with respect to local time (LT) of observation, however, a possible dependence of lower altitude on LT of observation was also found, indicating a near-constant penetrating path-length in the upper atmosphere for each train. The average upper altitude of persistent Leonid trains was 99.8 km, while the average central altitude was 93.0 km. These trends are probably determined by atmospheric conditions such as the abundance of O and O₃.

Keywords: Imaging, Leonid, METRO campaign, persistent meteor train, triangulation

1. Introduction

Persistent meteor trains appear as a luminescent cloud that is visible immediately following the occurrence of very bright fireballs of magnitude -4 or brighter. Opportunities for observing persistent meteor trains are limited by the rarity of fireballs of sufficiently intense brightness. Even if a persistent train occurs in the clear night sky, the faint luminescence of the train is usually only visible for a few tens of seconds because of the rapid rate of diffusion in the upper atmosphere. Leonid meteor storms occur at 33-year intervals related to the perihelion return of the mother comet Tempel–Tuttle. Experimental studies have demonstrated that the occurrence of bright fireballs within the Leonid meteor storm is greater than within other meteor showers. The rapid incident velocity of Leonids (71 km/s) makes the Leonid storm period an ideal time to observe persistent meteor trains. Recent advances in the prediction of the occurrence of meteor showers (e.g. McNaught and Asher, 1999; Lyytinen and Van Flandern, 2000) enabled the METRO campaign to observe meteor showers at precisely predicted times and dates.

2. Observation Methods

The METRO campaign involved amateur observers recording persistent meteor trains using a well-refined observational manual based on the optimum photographic conditions determined by previous observations (Toda et al., 2003). During the early 1990s, Leonid fireballs were so rarely observed that the optimum conditions for imaging persistent trains were largely unknown, however, it is now known that persistent trains can be photographed using simple cameras with a wide-aperture lens ($F/2.8$ or brighter) and high-sensitivity films ($ISO = 1600$ or larger) if the camera field of view is centered on the meteor train immediately following the appearance of the associated fireball. Simultaneous observation of meteor trains at multiple sites requires highly skilled collaborators and long observational periods in order to capture the rare occurrences of magnificent fireball events. During 1988–1997, prior to the METRO campaign, photographic images of persistent trains were limited to several photographs of short exposure times of about 5 s per frame, but several multi-site observations of persistent trains were recorded. During the METRO campaign, guidelines for meteor train observation were widely distributed to collaborators throughout Japan via scientific meetings, articles, and web sites. As a result, many amateur astronomers were able to photograph the meteor trains using the optimum settings for their individual cameras. Recently, digital cameras and image-intensified video cameras have been used to record meteor trains, providing images of high temporal resolution.

3. Results

The METRO campaign resulted in the collection of more than 400 image sequences (5000 snapshots) of Leonid persistent trains during the period 1998–2002, as well as persistent train images related to the Orionid, Taurid, Perseid, Geminid, Quadrantid, and sporadic meteors during the period 1988–2004. Most of the image sequences are summarized in the two catalogue papers of persistent train images (Toda et al., 2004; Higa et al., 2005) as well as on the METRO web site (Yamamoto et al., 2005). The 53 multi-site observations of Leonid and Orionid persistent trains are also archived in the image database.

Here, the altitudinal distribution of 20 persistent meteor trains is determined using archived METRO campaign data. The METRO archives contain contributions from many independent collaborators, and the archive consequently contains many images of low spatial and temporal resolution that are unsuitable for detailed analysis, however, statistical analyses of persistent train morphology with microstructures have been undertaken (Higa et al., 2003, 2005). In order to obtain precise estimates of altitudinal distribution, triangulation data from the 20 selected meteor trains had to meet the following criteria: the distance between two or more observational sites was > 30 km, train images were clear, observations were of high spatial and temporal resolution, both the upper and lower terminations of each persistent train were imaged within the field of view and not obscured by cloud, and time consistency was achieved between the multiple observations. The altitudinal distribution of persistent meteor trains, including 2 Orionid trains, was determined (Table I) in combination with the data of Urasaki (1988), Suzuki et al. (1989), Suzuki (1998), Shigeno et al. (1998), and Yamamoto et al. (2003). The central altitude of each train was in the range 87–99 km, while the upper and lower altitudes were in the ranges 95–109 km and 75–94 km, respectively.

4. Discussion

The triangulation method for determining meteor trajectory from multi-site photographic observations has been developed by many researchers, although this method is unable to resolve the spatial position of persistent meteor trains. This is because the linear trajectory assumption involved in the calculation of meteor trajectory cannot be applied to the analysis of persistent trains due to their complex and rapidly varying three-dimensional structure. In this study, triangulation analysis involved capturing the upper and lower ends of the meteor train at multiple observational sites. Problems exist in attaining time consistency between the different image sequences, as

TABLE I
Altitudes of simultaneously observed persistent trains

Train No.	Date	Local time (JST)	Meteor shower	Profile of parent fireball		First detection time [s]	Persistent altitude	
				Brightness [mag.]	Upper [km]	Lower [km]	Upper [km]	Lower [km]
1988-1	Oct. 22, 1988	4:04:02	Orionids	-4	-	-	100	84
1988-2	Oct. 22, 1988	4:08:41	Orionids	-6	-	-	109	88
1995-1	Nov. 19, 1995	1:38:00	Leonids	-6	-	270	101	86
1996-1	Nov. 17, 1996	4:11:27	Leonids	-5	-	-	98	88
1996-2	Nov. 17, 1996	5:15:50	Leonids	-8	-	-	100	75
1997-1	Nov. 18, 1997	2:42:26	Leonids	-5	-	-	102	89
1998-1	Nov. 18, 1998	4:13:55	Leonids	-8	177	78	95	81
1999-1	Nov. 19, 1999	1:36:25	Leonids	-5	118	89	96	91
1999-2	Nov. 19, 1999	4:26:24	Leonids	-5	-	-	97	93
2000-1	Nov. 19, 2000	3:35:31	Leonids	-6	118	83	103	85
2001-1	Nov. 19, 2001	1:36:33	Leonids	-4	-	-	100	85
2001-2	Nov. 19, 2001	1:47:24	Leonids	-8	155	79	95	89
2001-3	Nov. 19, 2001	2:01:26	Leonids	-3	-	-	106	91
2001-4	Nov. 19, 2001	2:17:28	Leonids	-6	-	-	99	88
2001-5	Nov. 19, 2001	2:42:21	Leonids	-4	-	-	103	88
2001-6	Nov. 19, 2001	3:02:18	Leonids	-3	-	-	97	83
2001-7	Nov. 19, 2001	3:28:56	Leonids	-3	-	-	98	91
2001-8	Nov. 19, 2001	4:06:44	Leonids	-4	-	-	104	79
2001-9	Nov. 19, 2001	4:27:12	Leonids	-3	-	-	101	85
2001-10	Nov. 19, 2001	4:55:47	Leonids	-6	-	-	101	86

Note that “first detection time” represents the time when consistent multi-site observations were firstly established.

observers at different sites were not able to synchronize their shutter timings. The rate of error in altitude estimate for each triangulation analysis is dependant on the spatial resolution of the photographs, the accuracy in determining the locations of objects in the photograph including lens distortion, the exposure time of each image, the accuracy of exposure timing at each site, and the spatial reconstruction of common points imaged at multiple observation sites. The residual altitude error for each analysis was within ± 2 km. The error involved in determining the lower altitude estimate is within ± 1 km, which is less than that of the upper altitude estimate because at higher altitude the train image is more diffuse due to the rapid diffusion speed of the luminescent train into the background atmosphere. In the observational manual of the METRO campaign, it was noted that the cameras should be moved onto a persistent train as quick as possible just after it appeared. This method completely eliminates height bias in the triangulation, since the entire (not the partial) train is presumably in the field of view of both multi-site cameras.

The average central altitude of the Orionid and Leonid trains are 95.3 km and 93.0 km, respectively. The altitudinal range of Orionid trains is slightly higher than that of Leonid trains, although it must be emphasized that only 2 Orionid trains were observed. Although the METRO campaign did not involve the compilation of information concerning the parent fireballs, the altitudinal distributions of parent fireballs analyzed by Sekiguchi (1998), Ohtsuka and Shimoda (1999), Sekiguchi (2000), and Sekiguchi (2001) were previously distributed via a local mailing list of the Nippon Meteor Society. Altitude data for parent fireballs related to 4 Leonid persistent meteor trains are shown in Table I. The upper altitude of persistent trains generated by these fireballs was almost constant at about 95 km, while the upper altitudes of two bright fireballs of magnitudes -8 were recorded at altitudes in excess of 150 km.

Figure 1 shows the altitudinal distribution of 18 Leonid meteor trains plotted against T_c (the time from initial appearance of the associated fireball). Each triangulation was carried out at the time that multi-site observations of the train were first realized. If multi-site observations were established soon after the appearance of the fireball, the true upper altitude of the persistent train could be determined prior to dissipation of the luminescence. A wide range in the altitude of persistent trains is obtained for $T_s < 20$ s, which corresponds well to the typical duration time of the molecular phase of train luminescence (Borovička and Koten, 2003). Accurate measurement of the lower altitude of the persistent trains is also dependent upon observation immediately following fireball activity.

Recent spectrum analyses of persistent trains reveal that during their early stages the trains are characterized by molecular emissions that gradually evolve into continuum emissions. Abe et al. (2005) presented a detailed

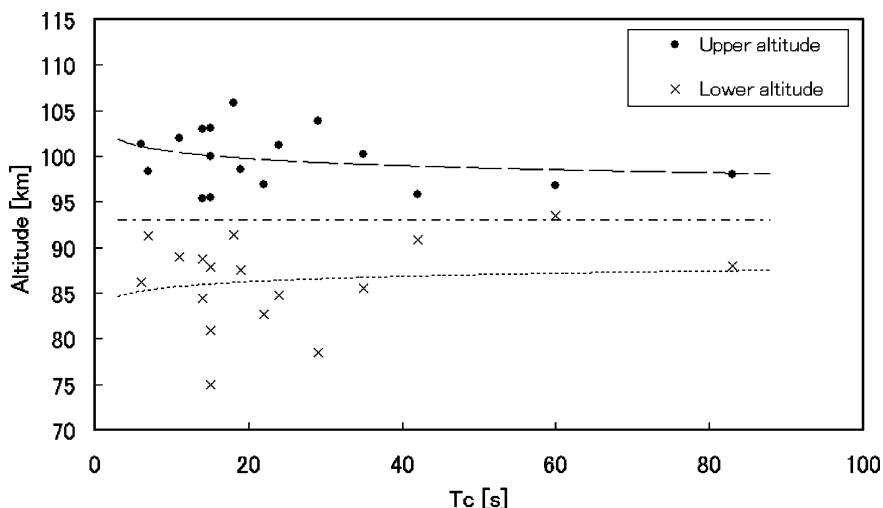


Figure 1. Altitudinal distribution of 18 Leonid persistent trains plotted relative to the time delay T_c from the initial appearance of the fireball related to each train observation. Dots and crosses represent upper and lower altitudes, respectively.

spectrum evolution of the persistent train “2001–2” listed in Table I. The long-lasting emission of persistent trains during the continuum phase is maintained by chemical reaction cycles between Fe and O_3 and between FeO and O (Jenniskens et al., 2000; Borovička and Koten, 2003). The average center altitude of ~ 93 km, which is statistically stable over time (Figure 1) is probably determined by altitudinal profiles O_3 and O concentration because a continuous supply of O_3 and O is necessary for the continuous chemical reactions that sustain persistent train luminescence. The relationship between the altitudinal dependence of 18 Leonid persistent trains and the magnitude of the associated fireballs shows a diffuse profile (Figure 2), although it must be taken into account that the magnitude estimates determined by visual observation are somewhat ambiguous.

Finally, there is no clear relationship between the local time (LT) of the events and the upper altitude of observed trains, while the measured lower altitude shows signs of LT dependence within a variation of ± 5 km (Figure 3). The typical upper altitude of the 18 observed Leonid persistent trains is ~ 100 km, with the same variation of ± 5 km, and this indicates that the upper altitude of persistent trains is largely controlled by conditions in the upper atmosphere. The possible LT-dependence of the lower altitude of observed trains probably results from the increasing elevation angle of the Leonid radiant point during the period 0000–0600 h LT, indicating a possible dependence on the penetrating path-length of the parent meteor. The small elevation angle at 0100 h results in rapid fragmentation near the upper altitude of each train, for instance. At the time of the larger elevation angle at

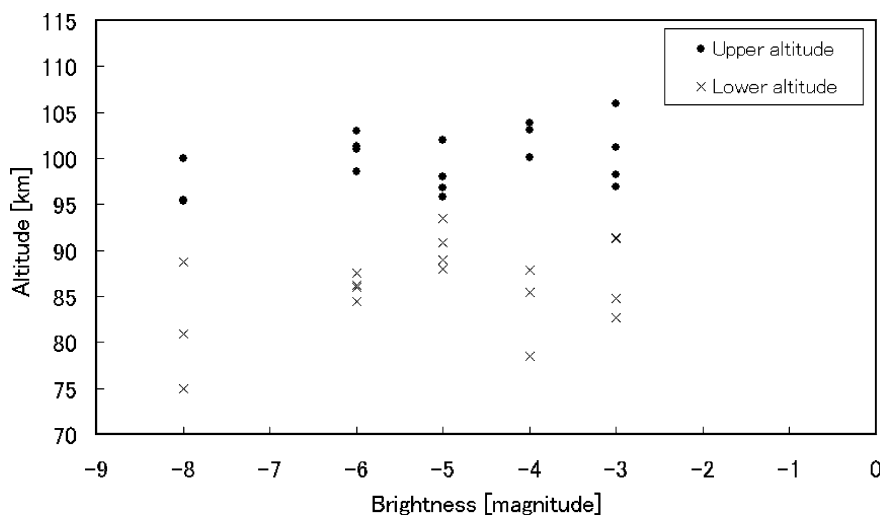


Figure 2. Relationship between the altitudinal distribution of Leonid persistent trains and magnitude of fireball brightness. Dots and crosses represent upper and lower altitudes, respectively.

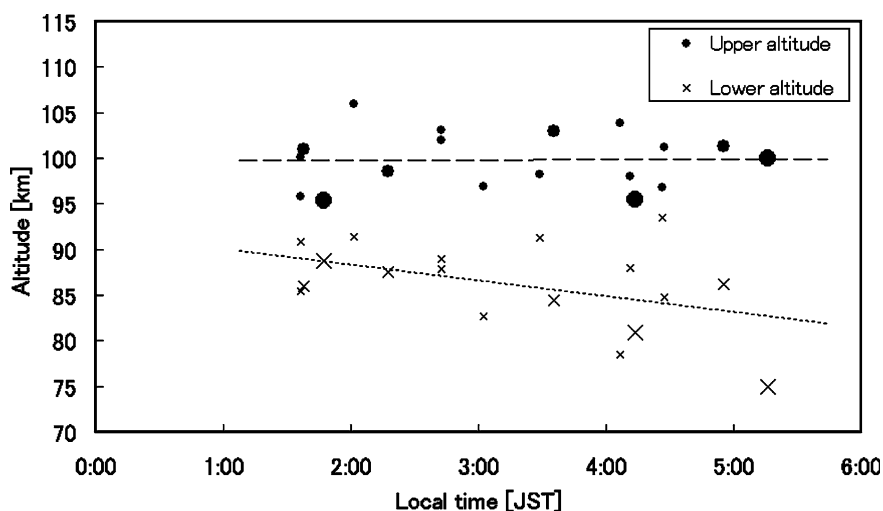


Figure 3. Relationship between the altitudinal distribution of Leonid persistent trains and local time of observation. Dots and crosses represent upper and lower altitudes, respectively. Large, medium, and small symbols indicate the brightness of the associated fireball of magnitudes -8, -6, and -5 or darker, respectively.

0500 h LT, each meteor could penetrate into the lower atmosphere at a constant path-length. The penetrating path-lengths of 18 Leonid trains are within the range 8–27 km; no clear dependence on the elevation angle of Leonid radiant is observed.

The present study presents triangulation analyses of 20 persistent meteor trains using accurate observation data from the METRO campaign archives. Although there are more than 30 examples of simultaneous multi-site photographic observations of persistent trains in the METRO campaign database, determining a method of analyzing this data is made difficult by the large number of contributing observers. Limitations to a detailed analysis of the archived data include: (i) the fact that not every observer provided a complete dataset of each observation, (ii) the difficulty in synchronizing the timing of observations from multiple sites, and (iii) the spatial resolution of observations was generally quite low. In order to utilize the lower resolution datasets, a more sophisticated analysis method should be implemented in the near future that enables determination of three-dimensional structures, diffusion, and turbulence of Leonid persistent trains as well as information concerning winds in the upper atmosphere.

5. Conclusions

The altitudinal distribution of Orionid and Leonid persistent meteor trains are provided for 20 observations documented by the METRO campaign and local publications prior to the campaign. The altitude of all trains is within the range 75–109 km. The altitudinal range of 18 observed Leonid persistent trains is slightly lower than that of the 2 observed Orionid trains. The average upper, central, and lower altitudes of the 20 simultaneously observed persistent trains are 100.3, 93.3, and 86.2 km, respectively. The typical upper altitude of Leonid persistent trains is about 99.8 km, while the average center altitude of persistent trains was about 93.0 km; this latter figure is probably determined by the atmospheric abundance of O_3 and O . No clear local time dependence was found for the upper altitude of the 18 Leonid examples, however, the lower altitude shows signs of local time dependence. This feature indicates that bright meteors generate source species of persistent train luminescence in the upper atmosphere along a constant penetrating path-length of about 20 km.

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SEARCHING FOR LIGHT CURVE EVIDENCE OF METEOROID STRUCTURE AND FRAGMENTATION

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Abstract. We used light curve analysis to search for evidence of the dustball meteoroid model. Leonid, Taurid, Alpha Monocerotid and sporadic meteors from November 2003 were observed and analyzed using uniform methodology. Meteors from these four sources were examined for evidence of fragmentation by examining light curve shape and searching for light curve irregularities. Differences in meteoroid structure should be reflected by differences in meteor light curves. The resulting meteor light curve F -parameter values showed no statistically significant differences between the meteors from the various cometary showers or the sporadic meteors. The F -parameter values also suggest that the meteoroids from these sources do not follow a single body ablation model, which suggests that all four sources produce meteoroids with a dustball structure.

Keywords: Dustball, fragmentation, light curve, meteor, meteoroids

1. Introduction

Meteor light curves measure the luminous intensity of meteors over time and can give valuable insight into the physical and chemical composition of meteoroids. It was observed by Jacchia (1955) that light curves for faint meteors often display anomalous properties which could be explained by progressive fragmentation. These fragmenting meteoroids were termed dustballs. A quantitative dustball ablation model was proposed by Hawkes and Jones (1975) in which elementary grains are coupled together by another more volatile substance. Babadzhanov (2002) provides a summary of potential modes of dustball ablation. Light curve analysis has proven a valuable technique for investigating meteoroid structure (Fleming et al., 1993; Campbell et al., 1999; Murray et al., 1999, 2000). While not the only means of substantiating and quantifying the dustball model (Fisher et al., 2000), light curve analysis has remained one of the most important.

By analyzing light curves of meteors of known origin, we can potentially learn about the composition and physical structure of parent objects. In this work we use light curve analysis for meteors from several different parent

objects under common observing conditions and with uniform analysis methods. This study analyzes light curves from meteors belonging to the Leonid, Taurid and Alpha Monocerotid meteor showers, as well as sporadic meteors. While the parent bodies of the Leonids (55P/Comet Temple-Tuttle) and the Taurids (2P/Comet Encke) are well established, the parent object of the Alpha Monocerotid meteor shower is not known conclusively, although it is probably cometary.

2. Data Acquisition

The meteors analyzed in this study were recorded over a three night period from November 16–19, 2003 from Sackville NB Canada ($64^{\circ} 22' \text{ W}$, $45^{\circ} 54' \text{ N}$). Two image intensified video rate monochrome CCD detection systems were used. ITT Gen III and Litton Nitemate Gen III Microchannel Plate (18 mm diameter photocathode) image intensifiers were coupled optically to Cohu 4910 30 fps NTSC CCD cameras. The Cohu CCD employed microlens technology in order to essentially eliminate dead zones between CCD pixels. The ITT Gen III was equipped with a 25-mm focal length, $F/0.95$ objective lens which resulted in a $20.9^{\circ} \times 27.8^{\circ}$ field of view. The Litton Nitemate Gen III was equipped with an 85 mm focal length, $F/2.0$ objective lens resulting in a $6.1^{\circ} \times 8.1^{\circ}$ field of view. All data were recorded digitally using Sony Digital-8 technology. MeteorScan 2.2 (Gural, 1999) was used in calibration mode for detection, shower association and magnitude determination.

3. Light Curve Analysis

In order to provide a first order field flattening and to remove artifacts due to stellar sources, we subtracted a near in time video frame from the frame containing the meteor. This technique, while not a full flat field correction, does provide a first order flattening of the response (Hawkes et al., 2001; Brosch et al., 2004). We did not use in the analysis any light curves from the extreme edges of the field of view where this correction technique is least complete. The video frame subtraction could not be a simple subtraction since that would have introduced bias related to the fact that the image analysis software (NIH Image) used unsigned integers to represent images. We eliminated this potential bias by applying an image inversion, offset and multiplication by a scaling factor to ensure frame subtraction without numerical cutoff artifacts. Tests of the image intensifier-CCD combination indicated that pixel to pixel variations were very small, much less than image to image variations. As will be described below, our technique uses values

from a number of pixels which further reduces any tiny pixel to pixel intensity variation.

Most conventional light curve analyses (e.g. Fleming et al., 1993; Campbell et al., 1999 Murray et al., 1999) have been done using intensities measured over a region of interest around the complete meteor luminosity in each video frame. With that approach each light curve only contains typically 6–15 luminosity values. In contrast, this analysis used a number of intensity readings in each video frame, one reading for each line of pixels over which the meteor moved. The resulting data set consequently contained many more data points than conventional light curves, ranging from several tens to several hundreds of data points for each light curve. Potentially this allows us to look at short term irregularities on meteor light curves.

A typical meteor light curve is shown in Figure 1. While such light curves appear to show very short scale light curve irregularities, the dual coincidence studies by Hawkes et al. (2001) have shown that most such features are not inherent light curve fluctuations. Some of the short scale irregularity is due to the interlaced scan system used by the CCD camera. To reduce these artifacts we applied a digital low pass filter in the form of a 3-sample boxcar integrator. While a larger sample boxcar would further smooth the light curves, we were concerned that it might also eliminate true variations in the light curves. We found that a 3 sample integrator was a good compromise which effectively removed the variation due to the interlaced scan while maintaining potentially significant variations. The same meteor of Figure 1 is shown after this smoothing in Figure 2. To examine possible fragmentation in the meteors a measurement of the skew of each smoothed light curve was performed. This was done by first carrying out a regression using the smoothed

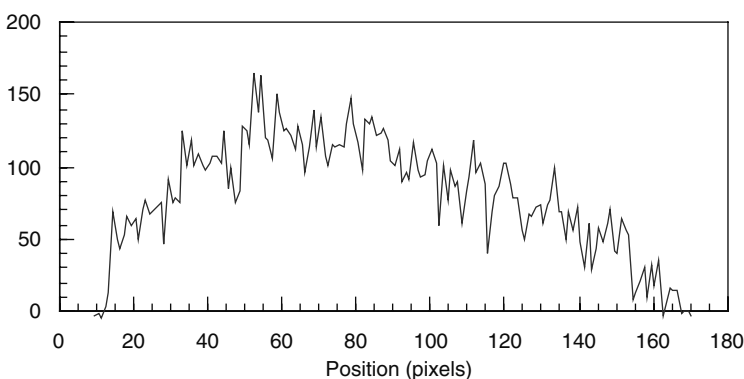


Figure 1. A typical meteor light curve (Nov 17 2003 at 06:11:04 UT captured with the Litton Nitemate intensified CCD with intensity (arbitrary scale) plotted versus position along the trail in pixels. Each point represents one intensity value which has been obtained by integrating over the width of the meteor trail at that point. Local background intensity values have been subtracted. The right hand side of the graph represents a later time in the meteor sequence.

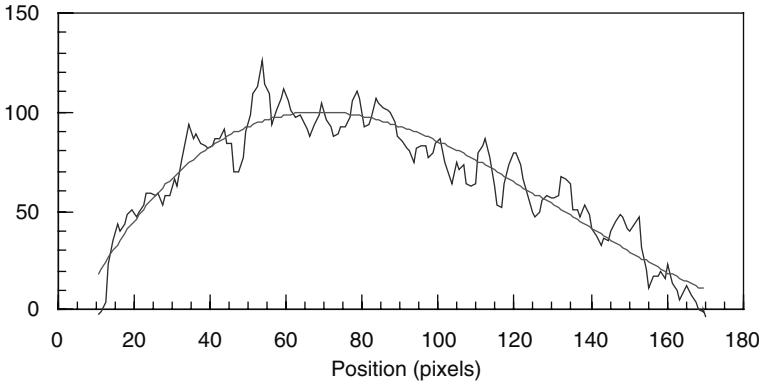


Figure 2. The same meteor as Figure 1 but after a 3 sample boxcar integrator applied to provide a modest amount of smoothing to remove artifacts due to the CCD NTSC video scan process. The smooth curve shows application of the fitting function and normalized to a peak intensity value of 100.

intensities versus displacement values with terms up to and including third order. The smoothed data sets were normalized to a fixed maximum intensity of 100 to enable a standard comparison between shapes of meteors of different intensities. The same meteor of Figure 1 is shown normalized and smoothed in Figure 2.

Previous studies (e.g. Fleming et al., 1993, Murray et al., 1999) have used the F ratio as a measure of the skew of meteor light curves. The F -value is the ratio of the distance to the position of maximum luminous intensity over the entire length of the light curve. We altered the conventional F -value slightly in using the 25% intensity and 50% intensity values, rather than a certain magnitude decrease.

$$F_f = \frac{x_{bf} - x_{\max}}{x_{bf} - x_{ef}} \quad (1)$$

In the equation F_f is the F -parameter at some fraction f of the maximum luminous intensity, $x_{\max}$ is the position of maximum intensity on the light curve, and x_{bf} and x_{ef} are the beginning and ending positions for an intensity value which is f times the peak light curve intensity. The resulting F -parameter values indicate whether the meteor achieved maximum brightness early in its trail, $F < 0.5$, or late in its trail, $F > 0.5$. For this study F -parameter values were calculated for intensities at 0.25 and 0.50 of maximum brightness.

4. Results

If a meteoroid is composed of a single, solid particle the light curves obtained would exhibit a slow rise to maximum brightness with a quick decrease

(Campell and Koschny, 2004). The majority of the meteors examined in this study do not follow this model, with on average the peak intensity values occurring near the midway point. The F -parameter values for points with one-half maximum intensity and one-quarter maximum intensity for each meteor shower as well as for the sporadic meteors are summarized in Table I.

5. Discussion

While the sample size is modest, this study represents an interesting comparison between sporadic and shower meteors collected at the same time with identical equipment and with the same analysis procedures applied. In a larger sampling of shower meteoroids (Koten et al., 2004) a mean F -value of 0.498 ± 0.014 was found for the Leonids, in excellent agreement with the value of 0.513 ± 0.026 for the Leonids from this research. For the Taurids, Koten et al. (2004) find an F -value of 0.535 ± 0.025 compared to a value of 0.532 ± 0.018 in this work, again in excellent agreement.

The results reported in the current study do not indicate any statistically significant differences between the light curves of the meteors from the cometary showers studied, or with the sporadic meteors, which would suggest that most of the sporadic meteors examined are of cometary origin. The results indicate that the meteors studied attain maximum brightness near the halfway point in their trail. From this we can conclude that the meteoroids do not follow single body ablation models and some form of dustball model is probably required (Fisher et al., 2000).

The meteor light curves analyzed in this study show an interesting similarity between meteors from different parent bodies. This would suggest that, for these cases at least, the composition and structure of these comets does not vary considerably. Also, since the sporadic meteor light curves are similar, it seems to suggest that the physical structure of meteoroids is not significantly altered by erosion or radiation effects while in space.

TABLE I

Results for the mean and standard deviation of the mean for F -parameter values at 0.25 and 0.50 of maximum brightness

Shower	N	$F_{0.5}$	$F_{0.25}$
Taurid	11	0.532 ± 0.018	0.559 ± 0.019
Leonid	6	0.513 ± 0.026	0.524 ± 0.031
Alpha Monocerotid	6	0.516 ± 0.033	0.553 ± 0.037
Sporadic	17	0.504 ± 0.021	0.489 ± 0.026

N is the number of meteors from each shower used in the analysis.

Recently Campbell-Brown and Koschny (2004) and Beech and Murray (2003) have indicated how light curve shape can be related to the type of mass distribution of the dustball grains. For example (Beech and Murray, 2003) assumed that the grains making up a dustball meteor follow a power law distribution on mass $m^{-\alpha}$. Their model allowed, for Leonid meteors, F -values between 0.46 and 0.62 (it should be noted that they defined F -values for points 1.25 astronomical magnitude below peak intensity, not exactly the same as the percentage of peak intensity reported here). If we use their model, an α value of 1.65 provides the best match to our observed data for the Leonid shower.

One advantage of the technique used here is that enough points are provided in each light curve to allow searches for high frequency oscillations related to ablation of shell like structures (Campbell-Brown and Koschny, 2004), rotation of the meteoroid, or possibly differential ablation (von Zahn, 2001). In much brighter meteors flickering has been observed and characterized (Thuillard, 1996; Beech, 2001). To this aim we have begun to apply the Discrete Fourier Transform to investigate periodicity of the meteor light curves. We will report on that work in a subsequent paper. It may also be possible to confirm the short sharp peaks in light curves (Jiang and Hu, 2001).

As the final form of this paper was being written, Brosch et al. (2004) published an interesting paper considering what parameters are most relevant for meteor light curve characterization. While that work supports the importance of F -values, other measures are also important. The analysis done here could readily be adapted to take into account some of their other parameters, such as measures of sudden change in the meteor light curves.

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ARIETID METEOR ORBITS MEASUREMENTS

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Abstract. The Arietid meteor shower is one of the strongest of the year. The origin of this daytime shower is unknown; the orbit is therefore of great interest, since an accurate orbit distribution is needed to integrate the shower backward in time to test associations with comets or asteroids. The orbital parameters of the Arietid shower as a function of time, with errors, have been generated using 415 radar orbits gathered at the CMOR facility in Tavistock, Canada.

Keywords: Meteors, radar, meteor shower

1. Introduction

The Arietid meteor shower is of great interest, since it delivers more meteoroids to the Earth during a typical year than any other shower. Historically, because radar observations are much less precise than photographic observations, the orbit of this daytime shower has not been determined with very high accuracy. The parent object of the Arietids is not clearly determined, though Comet 96P/Machholz has been linked to it (Babadzhanov and Obrubov, 1992; Jones and Jones, 1993), so an accurate orbit is essential. One way to get an accurate orbit from radar data is to use the orbits of many meteors.

We present here the best recorded orbits for 2002 and 2003 at the CMOR (Canadian Meteor Orbit Radar) facility in Tavistock, Ontario, Canada. In particular, we wish to see how the orbit changes as a function of time, and to measure the spread in the orbital parameters. In our previous work (Campbell-Brown, 2004), we calculated an average orbit using a computed velocity at the top of the atmosphere and the change in the radiant as determined from a statistical analysis of single station radar data. In the current work, we use a recently computed relation to calculate the deceleration of individual Arietid echoes, for which we can then calculate individual orbits. While the average orbit can be used to look at the general properties of the stream as the Earth passes through it, it is also of interest to investigate the spread in orbital parameters, which has some bearing on the history of the stream.

2. Observations

Details of the CMOR radar can be found in Jones et al. (submitted). The radar operates at three frequencies, each with its own interferometer placed at the main site; at the middle frequency (29.85 MHz) it has receivers placed at remote stations 8.1 and 6.2 km from the transmitter. In the current work, we used only echoes recorded on the 29.85 MHz system which were detected at both remote stations, and for which velocities could therefore be computed. Those echoes were selected which were within 10° of the Arietid radiant for a given day, the radiant being found through single station observations described in Campbell-Brown (2004). No velocity discrimination was used. Some sporadic meteors will be counted by this process: the average number of meteors in the radiant box after the shower was 350, compared to 1200 at the peak time. This will tend to introduce errors in the average orbital parameters particularly at the beginning and end of the shower, when the number of Arietids is comparable to the number of sporadics.

A total of 1104 orbits were found in 2002 and 2003. All of these have a velocity associated with them, but some errors are introduced in the technique due to noise on the system. The velocity is found using the time intervals between echoes recorded at the main station and each of the remote stations; as a reference point, the point of maximum curvature on the rise of the echo is measured for each station. If the reference point on each echo is not chosen identically on each system, the velocity will be in error. To ensure that only the best velocity measurements were used, each echo was examined by hand, and echoes were eliminated for which there was some question of the correct reference point being selected at either remote station. This rather stringent criterion left only 415 orbits.

3. Orbit Calculations

The first step in calculating orbits for each meteor is to estimate the deceleration for each echo. We used the formula of Brown et al. (2005), which gives the deceleration as a function of observed velocity and height:

$$\Delta v = (-0.005098v_m + 0.5142) \cdot [h - (0.3362v_m + 86.6039)] \quad (1)$$

where Δv is the change in velocity, v_m is the measured velocity, and h is the height in km. The relation was derived empirically using the average observed speed of many showers of known speed as a function of height. In general, the lower a meteor is observed in the atmosphere, the greater the deceleration.

The average corrected velocity as a function of solar longitude is shown in Fig. 1, with the value of 39.4 km/s (calculated for the whole sample in the previous paper) shown with a solid line. There is no significant dependence on time.

4. Results

Using the observed radiant and the corrected speed, orbits were calculated for each meteor using code written by Ceplecha (1987). The results are compared to the average orbital parameter motion in Fig. 2. The standard error is shown by the error bars for each day. The slight offset in the argument of perihelion and to a lesser extent in the perihelion distance are probably due to the smaller sample size: the radiant used in the previous calculation was an average of all single-station meteors from three years of data, a total of several thousand meteors. Small differences in the radiant may have caused the differences seen in this data set. The differences amount to a twisting of the orbits by 2 or 3°, and likely reflect the total uncertainty in the orbital parameters rather than a difference between the meteors captured by single station and those for which orbits could be obtained.

The average orbital parameters at solar longitude 78.5°, the time of the peak, were determined using the echoes which occurred within 0.5° solar

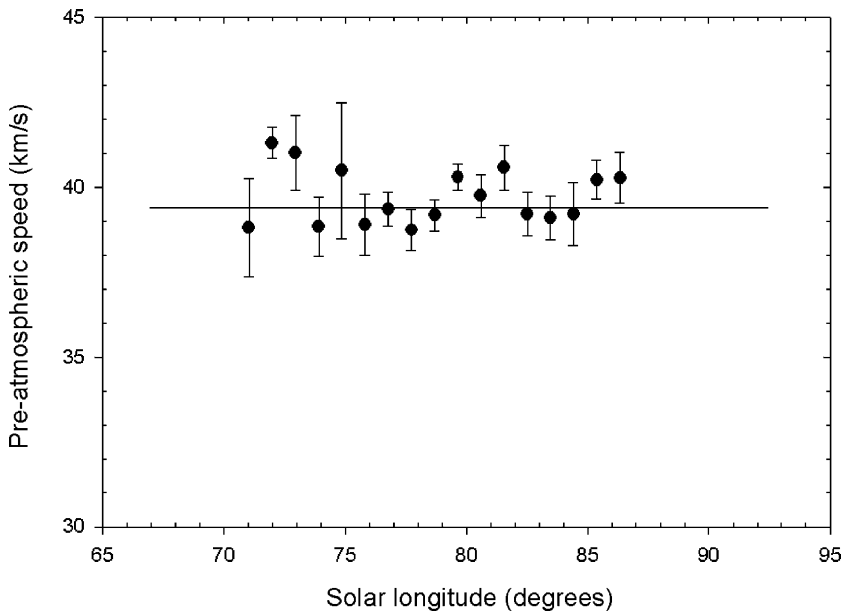


Figure 1. Pre-atmospheric speed of Arietids as a function of solar longitude. The solid line is the average value calculated in Campbell-Brown (2004).

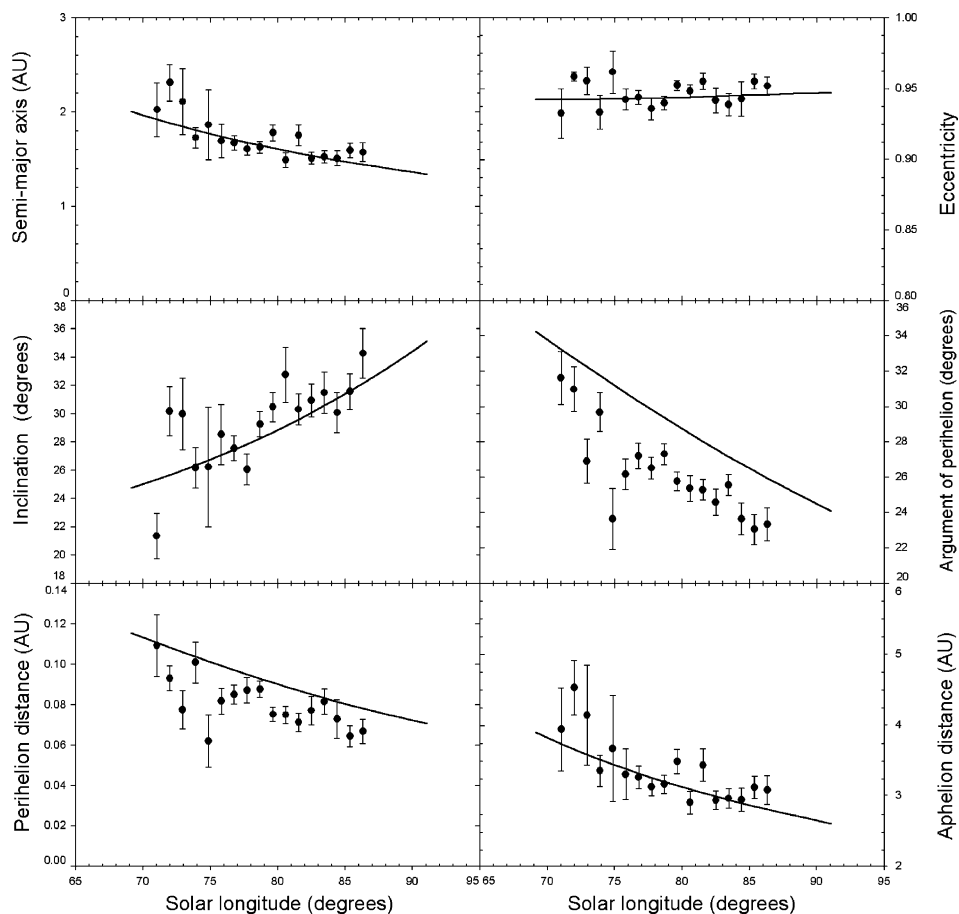


Figure 2. Arietid orbital parameters as a function of solar longitude. The solid lines are the previously calculated average for each.

longitude of the peak. They are as follows: semimajor axis a : 1.6 ± 0.4 AU; eccentricity e : 0.94 ± 0.03 ; inclination i : $29 \pm 6^\circ$; perihelion distance q : 0.88 ± 0.03 AU; aphelion distance Q : 3.2 ± 0.9 AU; argument of perihelion ω : $27 \pm 4^\circ$.

The average orbit at the time of the peak was compared with an extensive catalogue of comets, asteroids and meteor showers using both the D (Southworth and Hawkins, 1963) and D' (Drummond, 1981) criteria. These slightly different formulas measure the level of difference between two orbits. While the exact cutoff point is not generally agreed upon, $D < 0.2$ is on the higher end of the generally accepted value for the Southworth and Hawkins criterion, and $D' < 0.11$ represents a high limit for the Drummond criterion (for some reviews on choices of D limits, see e.g. Galligan (2001, 2003)). No single object matched the Arietids closely according to these requirements,

which is consistent with the shower being a very old one. Comet 96P/Machholz, which has been linked dynamically with the Arietids, had a D of 0.691 and a D' of 0.276. The comet may be associated with the stream, but the orbits are now significantly different. Interestingly, asteroid 1566 Icarus has a smaller D of 0.257 and a D' of 0.362; this object may be part of a family of bodies including Comet Machholz, though a chance association is also possible. The only other orbit remotely close to that of the Arietids belongs to the Monocerotid shower ($D = 1.564$; $D' = 0.618$), which has not been linked to Comet Machholz. Detailed modelling of all these bodies may reveal if they were more closely related in the past.

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METEOROID ABLATION MODELS

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Abstract. The fate of entering meteoroids in atmosphere is determined by their size, velocity and substance properties. Material from ablation of small-sized meteors (roughly $R \leq 0.01$ –1 cm) is mostly deposited between 120 and 80 km altitudes. Larger bodies (up to meter sizes) penetrate deeper into the atmosphere (down to 20 km altitude). Meteoroids of cometary origin typically have higher termination altitude due to substance properties and higher entry velocity. Fast meteoroids ($V > 30$ –40 km/s) may lose a part of their material at higher altitudes due to sputtering. Local flow regime realized around the falling body determines the heat transfer and mass loss processes. Classic approach to meteor interaction with atmosphere allows describing two limiting cases: – large meteoroid at relatively low altitude, where shock wave is formed (hydrodynamical models); – small meteoroid/or high altitudes – free molecule regime of interaction, which assumes no collisions between evaporated meteoroid particles. These evaporated particles form initial train, which then spreads into an ambient air due to diffusion. Ablation models should make it possible to describe physical conditions that occur around meteor body. Several self-consistent hydrodynamical models are developed, but similar models for transition and free molecule regimes are still under study. This paper reviews existing ablation models and discusses model boundaries.

Keywords: Ablation, meteoroids, modeling

1. Introduction

Cosmic bodies entering the Earth' atmosphere lose a part of their mass or even the total mass during the interaction with the atmosphere. The mass loss process is called ablation. Ionized and luminous areas, metal layers and smoke dust appear in the atmosphere due to ablation. Meteoric material is involved into the atmospheric chemistry (Dressler and Murad, 2001 and references therein), meteor spectra confirm appearance of Fe, Si, Mg, H, Na, Ca, Ni, Mn, Cr, Al, Ti, CN, FeO, AlO, MgO, OH due to ablation (Ceplecha et al., 1998). Meteors are sometimes considered as the source of organic material deposited into the atmosphere during ablation (Jenniskens, 2001).

Ablation is dependent on the meteoroid size and mass, the entry velocity, altitude of flight and meteoroid properties. The ablation rate determines the deposition of mass, influences the momentum and energy release into the atmosphere. Meteor radiation and ionization, which allows us to observe meteor phenomena, are also determined by the ablation rate:

$$I = \tau \left(\frac{V^2}{2} \frac{dM}{dt} + MV \frac{dV}{dt} \right) \quad \alpha = \frac{\beta}{\mu V} \frac{dM}{dt} \quad (1)$$

where V , M are the meteoroid velocity and mass, τ is the luminous efficiency and β is the ionizing efficiency, α is the linear electron concentration, μ is the average mass of an ablated meteoroid atom and I is the intensity of radiation.

The range of meteoroids entering the Earth is extremely large; their masses varying from about $\sim 10^{-18}$ g up to asteroid-class impactors ($\sim 10^{15}$ kg). Meteor particles smaller about 10^{-4} cm ($\sim 10^{-15}$ kg) are not heated enough to ablate (see below). Meteoroids larger about Tunguska-sized (~ 100 m, $\sim 10^9$ kg) ones lost only small part of their mass and energy during their passage through the Earth's atmosphere. Ablation is essential for the meteoroids in the range of roughly 10^{-6} – 100 m. Note that the largest annual event is estimated to have initial kinetic energy of about $E \sim 5$ – 10 κT (Nemtchinov et al., 1997a; Brown et al., 2002) (i.e. meteoroid with mass about $M \sim 150$ – 300 t and ~ 2 – 2.5 m in radius).

The altitudes, where the ablation mainly occurs, are dependent on entry velocity; on the meteoroid origin and composition (cometary material is deposited higher than asteroidal matter); on size (larger bodies penetrate deeper). The ablated material is mainly deposited at the altitudes about 120 – 20 km (Rietmeijer, 2000); in extreme cases – from as high as 200 – 400 km (Spurný et al., 2000a, b; Brosch et al., 2001) down to the ground.

The physical conditions during the meteoroid entry change considerably as a function of altitude; the atmospheric density varies by about 10 magnitudes or larger (from 10^{-13} at 200 km altitude down to 10^{-3} g/cm³ at the ground). There are no complete self-consistent ablation models, which would allow following the total path for all meteoroid sizes through the atmosphere.

2. Energy Balance

The standard heat balance equation per unit surface area for spherical body under an assumption of an isotropic energy flux may be written as

$$\frac{1}{2} \Lambda \rho_a V^3 = 4\varepsilon \sigma (T_s^4 - T_0^4) - \frac{Q}{\pi R^2} \frac{dM}{dt} + \frac{4}{3} R \rho c \frac{dT_{av}}{dt} \quad (2)$$

where R is the meteoroid radius, Λ is the heat transfer coefficient, Q is the specific ablation energy (usually ablation is considered as vaporization, but it also may include other mechanisms, for example the sputtering); c is the specific heat, ρ_a , ρ are the atmospheric and meteoroid densities, ε is the emissivity, σ is the Stefan-Boltzmann constant, T_s , T_{av} , T_0 are the temperature of the meteoroid surface, some uniform temperature of the body and the ambient temperature.

This equation implies that the energy flux received from the impinging air molecules (left side) is treated to thermal radiation cooling (right side, first term), ablation (second term) and heat conduction (third term). Its detailed analysis may be found in Jones and Kaiser (1966), Lebedinets (1980), Moses (1992) and others.

At a given altitude the behavior of entering particles in the atmosphere is determined by their size, velocity and material properties. The smallest bodies ($\leq 10^{-4}$ cm, here all numbers are rough estimates for 30 km/s entry velocity) decelerate before being substantially heated. The heating of bodies with $R \leq 0.01$ cm is limited by thermal radiation. The heating of larger bodies ($R > 0.1$ cm) cannot be characterised by a uniform temperature T_{av} . For that case, thermal conductivity has to be included into consideration. The heated layer of the meteoroid is about $0.01 \div 0.1$ cm in thickness (Bronshten, 1983; Ceplecha et al., 1998).

The deeper the meteoroid penetrates into the atmosphere the larger will be the received energy flux. The altitude, at which the received energy flux becomes larger than energy losses on meteoroid heating and thermal radiative cooling, may be called the height of intensive evaporation. For porous bodies with $R \sim 0.1\text{--}10$ cm this altitude is about 110–130 km (Lebedinets, 1980; Bronshten, 1983; Ceplecha et al., 1998). Below this altitude the incoming energy contributes to ablation mainly; heat conduction and thermal radiation cooling are usually excluded from the consideration (Bronshten, 1983; Ceplecha et al., 1998).

The estimates given above do not include the energy and mass losses due to sputtering, a process, which is efficient mainly for fast meteors ($V > 30\text{--}40$ km/s). The estimates of the mass loss due to the sputtering effect were done by a number of authors under different assumptions (Levin, 1956, 1961; Opik, 1958; Lebedinets et al., 1973; Lebedinets, 1980). Recently it has been considered in a more detailed way (Hill et al., 2005; Popova et al., 2005; Vinkovic, 2005). We will also discuss some features of sputtering below.

Ablation may be influenced by meteoroid rotation (see Adolfsson and Gustafson, 1994 and references there). For small particles the effect of rotation becomes important when a meteoroid is large enough to sustain a temperature gradient. Beginning heights of meteor varies by 10 km depending on the rotation state of a meteoroid (Adolfsson and Gustafson, 1994). In the case of slow rotation the thermoconductivity decreases the surface temperature on the backside of meteoroid. With the altitude decreasing the time of the backsurface heating will decrease due to substantial increase of the incoming energy flux; the influence of thermoconductivity on ablation will tend to diminish. The rotation also provides the cross-sectional area variations and causes appearance of intensity modulations (Beech and Brown, 2000; Beech et al., 2003). All results given in this paper are obtained without taking into account the rotation.

3. Different Regimes of Meteoroid's Interaction with the Atmosphere

Two limiting cases are evident in the meteor's interaction with the atmosphere. If the meteoroid is small enough, or the altitude of flight is high enough the interaction of the meteoroid with atmosphere takes place in free-molecule regime. In this regime evaporated and sputtered material does not screen the meteoroid surface; there are no interactions of ablated atoms with each other. Large meteoroid at relatively low altitude (a shock wave is formed) is satisfactorily described by hydrodynamic models.

Local flow regime realized around the falling body determines the heat transfer and mass loss processes. The description of the flow regime may be done in terms of dimensionless parameters. The Knudsen number $Kn = l/R$ represents the ratio of molecule mean free path l to a characteristic body dimension R (Figure 1a). The free-molecule flow corresponds to $Kn > 10$, where interparticle collisions are negligible. As the atmospheric density increases, the mean free path decreases and that leads first to formation of a viscous layer and then to formation of a shock wave.

According to Figure 1a meteoroids with size $R \sim 0.1$ cm interact with the atmosphere under free flow conditions. However the Knudsen number for undisturbed air is insufficient for a description of air–meteoroid interaction because the appearance of reflected, and later evaporated, molecules will affect the situation. Flow regime boundaries are dependent both on size and velocity.

Bronshten (1983) suggested to modify Knudsen number and to take into account the increase in reflected and evaporated molecule concentration in comparison with number of incoming particles due to a difference between the meteoroid velocity and the velocity of reflected and evaporated

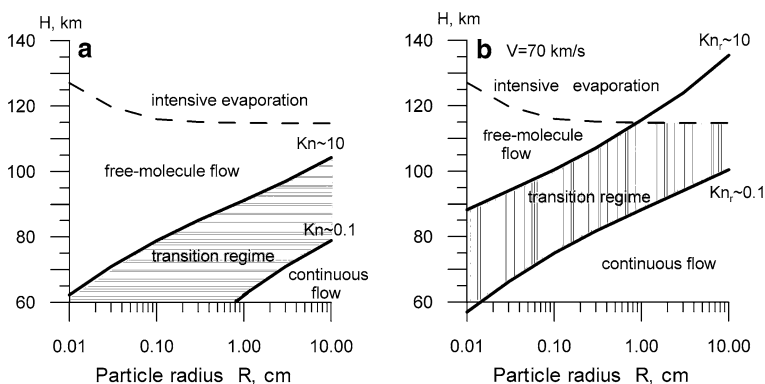


Figure 1. Boundaries of different flow regimes estimated with Knudsen number for undisturbed air (a) and taking into account presence of reflected/evaporated molecules (for $V \sim 70$ km/s) (b).

molecules V_r (which is determined by surface temperature): $Kn_r = (V_r/V)Kn$. This increase in density leads to a decrease in the mean free path. The boundary of pure free-molecule regime ($Kn_r \sim 10$) shifts to higher altitudes (Figure 1b, for meteor velocity 70 km/s). Below this boundary screening of the meteoroid surface by reflected and evaporated molecules should be taken into account. For the majority of Leonids the interaction takes place in transition regime from free-molecule flow to continuous one (Figure 1b).

Another estimate of the boundary between the free-molecule and transition regimes was done in Popova et al. (2000). The high velocity of fast meteors provides high evaporation rates and the pressure of formed vapor is higher than aerodynamical loading. That leads to the formation of a vapor cloud around the body and to subsequent vapor cloud screening. The boundary of pure free-molecular regime is shifted to higher altitudes.

4. Sputtering of Meteor Bodies

The bright Leonid meteors demonstrate extremely high altitude of radiation beginning up to about 200 km (Spurný et al., 2000a, b; Fujiwara et al., 1998). About one hundred of all registered meteors have beginning altitude above ~ 130 km. All these meteors have high entry velocities ($V > 46.5$ km/s), and the most of them are Leonids (Koten et al., 2003). For bright Leonids beginning altitudes in the range 130–150 km are quite usual (although less than in 5% of all detected meteors). Above 130 km altitude meteor images also show unusual diffuse comet-like structures (Spurný et al., 2000a, b). Radar echoes from Leonid meteors were recorded at altitudes up to 400 km (Brosch et al., 2001). Classical ablation theory, which assumes intensive evaporation following a temperature rise up to about 2000 K, does not explain meteor produced ionization and luminosity at altitudes higher about 130 km.

Sputtering effect was proposed as an explanation of ionized meteor trails and luminosity at high altitudes (Brosch et al., 2001). Above the altitude of intensive evaporation (~ 120 – 130 km) action of air particles on meteoroid leads to both heating of the meteoroid and sputtering of the meteoroid surface. Sputtering is the direct ejection of the particles from the material due to the surface's bombardment by energetic incoming particles and is not connected with the surface heating. In the case of small meteor bodies sputtering may lead to noticeable mass loss (Lebedinets et al., 1973; Lebedinets, 1980; Hill et al., 2005) and to the deceleration (Coulson and Wickramasinghe, 2003).

Meteoroid particles that had escaped from the meteoroid surface are suggested to penetrate far enough and hold enough energy to disturb the surrounding air. Flux of these particles causes formation of ionized meteor trails recording by radars. For the larger meteoroids fast particles may create a luminous area at the altitudes above altitude of intensive evaporation.

Recent work (Popova et al., 2005) showed that sputtering is essential for high velocity meteors ($V > 30$ km/s), and fast particles can carry out about 10–20% of incoming energy.

High altitude spectra of bright Leonids (above 120 km altitude) show emissions of O, Na, Mg, N₂. Oxygen and molecular nitrogen (O, N₂) emissions appear first in observations of the high altitude spectra (Borovička, personal communication).

Formation of oxygen triplet radiation at 777 nm, which occurs due to interaction of sputtered particles with the surrounding atmosphere, was considered (Popova et al., 2005). Brightness estimates for 10 cm body ($V \sim 70$ km/s) are compared with observations (Figure 2a). Model and observed light curves demonstrate similar dependence of the brightness on the air density. Larger meteor size is suggested than would be estimated with the help of the photometric mass. This estimate of the meteor brightness is a lower estimate because only first collisions of sputtered particles were taken into account.

Interaction of sputtered atoms with the atmosphere and formation of luminous area at high altitudes were also considered by Vinkovic (2005). He conducted DSMC (Direct Simulation Monte Carlo) modeling, taking into account only elastic collisions and assuming sputtering efficiency ~ 1 . He found that the initial particle energy is redistributed by secondary collisions and is enough to form a large disturbed area around the meteoroid. The shape of the disturbed area and its changes with altitude coincides with observations (Figure 2b).

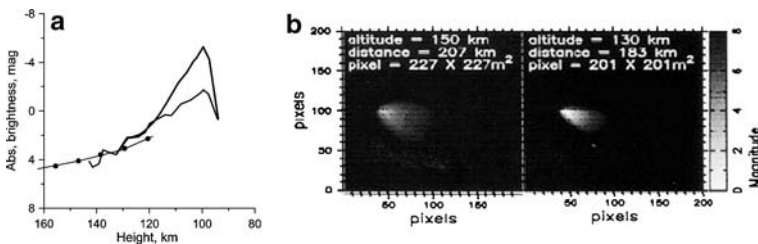


Figure 2. (a) Comparison of the model (Popova et al., 2005) (black pointed curve) and observed light curves (Koten et al., 2003); (b) modeled meteor at two altitudes (indicated at the frames together with pixel size and distance from the camera) (image due to courtesy Dr. Vinkovic).

5. Ablation Modeling in Free Molecule Regime

In free molecule regime air particles give all their energy to the meteoroid, the heat transfer coefficient $\Lambda = 1$, and one knows the ablation rate.

There are many studies that deal with the solution of standard equations of meteoroid flight under various assumptions about emissivity, vapor pressure dependences, etc. These considerations allow one to determine the fate of incoming material in the Earth atmosphere, to predict mass and energy deposition at different altitudes H (Flynn, 1989; Love and Brownlee, 1991; Hunten, 1997 and others); to predict ionization (for example Close et al., 2004; Hunt et al., 2004; Cervera and Elford, 2004); to consider meteors in different planetary atmospheres (Moses, 1992; Moses et al., 2000; Pesnell and Grebowsky 2000; Pesnell et al., 2004); to reproduce light curves (Campbell-Brown and Koschny, 2004 and others).

There are a number of questions, which still have no precise answers – what is the state of ablated material in this regime (its density, temperature, etc.), what are the luminous and ionizing efficiencies, what are the size and the shape of the luminous volume?

Several papers considered the interaction of evaporated atoms with the atmosphere. The initial radius theory reasonably well constrains the radio meteor data (Jones, 1995). Particle dynamics was considered in attempts to describe the head-echo formation (Jones et al., 1999). The estimates of ionizing and luminous efficiencies have still a limited velocity range and are restricted by usage of the cross-sections for iron atoms only (Jones, 1997; Jones and Halliday, 2001). There are no models, which describe the conditions in the luminous area and allow to predict spectra of meteor radiation.

An important question in meteor modeling is fragmentation and its role in ablation. The fragmentation is responsible for many differences between single-body model predictions and observations. Numerous studies have been carried out to show the influence of fragmentation on light curves and deceleration of small meteoroids (Jacchia et al., 1965; Simonenko, 1968; Lebedinets and Shushkova, 1968; Hawkes and Jones, 1975; Murray et al., 1999, 2000 and others) and different models (dustball, grain and others) were proposed. A comprehensive review may be found in Bronshten (1983) and Cepelcha et al. (1998).

A models of ablation of faint meteors was suggested by Campbell-Brown and Koschny (2004) for meteor with masses $M \sim 10^{-6} - 4 \cdot 10^{-2}$ g (i.e. with sizes about $R \sim 0.01 - 0.2$ cm), which are registered by radar and intensified video observations. They incorporated the dustball model by Hawkes and Jones (1975), assuming fragmentation in a form of grain release and ablation as two-stage evaporation. The interaction of the initial meteor and subsequent grains with the atmosphere is described in the free-molecule regime. Light curves of three Leonid meteors were successfully modeled, and the grain

distribution was determined. Grain masses are estimated as 10^{-4} – 10^{-8} g, that is in agreement with earlier results by Simonenko (1968), Murray et al. (1999, 2000).

A large set of head-echo observations was analyzed by Hunt et al. (2004) and Close et al. (2004). They estimated the mass and size range of their meteors as $M \sim 10^{-8}$ – 10^{-1} g, $R \sim 0.001$ – 0.3 cm (i.e. about the same range as in Campbell-Brown and Koschny, 2004). Similarity of model and measured distributions of electron density allowed the authors to conclude that fragmentation is not significant for those meteors.

Bellot Rubio et al. (2002) deal with slightly larger meteors of Jacchia et al. (1967) catalog with brightness of about $+2.5 - 5^{\text{mag}}$. They modeled about 370 meteors from this catalogue with masses of about $M \sim 10^{-2}$ – 10 g ($R \sim 0.1$ – 1 cm). The determined values of the ablation coefficient, bulk density of meteoroids were found in general agreement with the result of independent methods (Ceplecha et al., 1998). The authors conclude that 73% of considered meteoroids are described well in the frame of single-body theory and did not undergo severe fragmentation. By applying the quasi-continuous fragmentation model to the same photometric data the authors demonstrate that the results of modeling may be model dependent.

Differential ablation model was suggested for small meteoroids ($R < 0.01$ cm) in free molecule regime by McNeil et al. (1998; 2001). This model assumes that different elements are released from a meteor at different points of its trajectory (in dependence on volatility – Na–Mg–Ca for example). Lidar observations tend to show one of several metal atom at a given altitude (below $H \sim 105$ km) for about 1200 meteor trails (Von Zahn, 2001). Lidar observations demonstrated this effect even for larger bodies (~ 1 cm), that is possible if meteoroid is efficiently fragmented. Optical spectra agree with differential ablation for sodium in some cases (Borovička et al., 1999; Murray et al., 2000), but optical evidences are less than expected (Von Zahn, 2001).

6. Transition Regime

The formation of a vapor cloud around fast meteor bodies was considered by Popova et al. (2000) within the framework of the air beam model. The energy transfer during the penetration of the air into the layer of evaporated molecules may be described in a manner similar to that of radiative transfer assuming some effective mass absorption coefficient. In that case vapor can be described gasdynamically, whereas the incoming air flow is considered as the particles' beam, which energy is absorbed by the vapor (similar to the high energy ion beam in the inertial confinement fusion experiments). It was demonstrated earlier that the self-regulating regime is realised (Nemtchinov, 1967; Popova et al., 2000, 2001). Gas dynamics

cannot be applied to a nonablating body, but it may be used for an ablating one.

The particles' energy is absorbed both by the vapor causing its heating and expansion and by the meteoroid itself causing its evaporation. Modeling shows that a vapor cloud is formed around the body. The total size of a dense vapor cloud is about 5–10 times the body size (Figure 3).

Vapor parameters depend on meteoroid size, velocity, altitude of flight and composition. Near the meteoroid surface the vapor has the lowest temperature (Figure 3b), that is close to the evaporation temperature. Vapor temperature increases with body size R and with velocity V (in accordance with high temperature vapor spectral component behavior, Borovička, 1994). Vapor temperature also increases with decreasing altitude, so spectra should be altitude dependent. The density of the vapor is about 10^{-6} – 10^{-9} g/cm³ and rapidly decreases with distance from the body.

Monte Carlo modeling of air–beam interaction with vapor showed that the energy transfer into the vapor is provided both by fast air and several generations of recoil vapor particles. The energy deposition length is 7–10-times larger than the path length of the air particles in the vapor.

Determination of vapor parameters allows us also to model parameters of total luminous volume and to obtain first theoretical vapor spectra. These calculated vapor spectra show general agreement with observations (Popova et al., 2000, 2001).

Models need to be developed to determine more precisely the energy and momentum transfer from air to vapor; air–vapor mixing; to include air radiation and non-elastic collisions. Nevertheless, our consideration revealed the questions, which should be cleared up, allowed us to obtain qualitative picture and to estimate main flow characteristics.

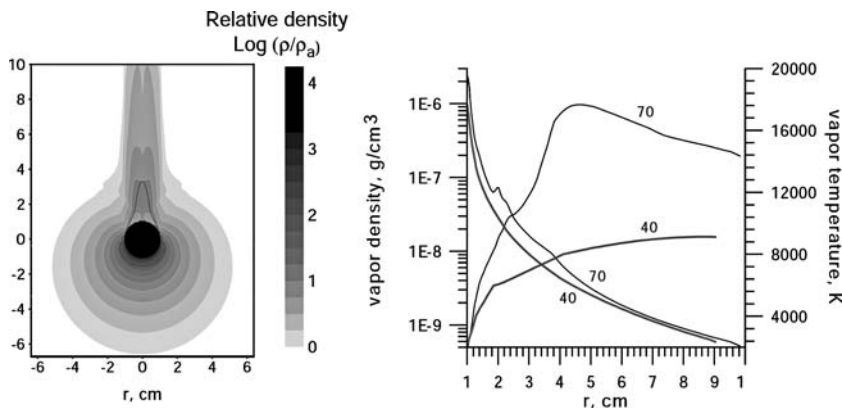


Figure 3. (a) Distribution of relative density around 1 cm body at 100 km altitude ($V \sim 70$ km/s). (b) Density and temperature of vapor in front of 1 cm meteoroid at 100 km altitude for $V \sim 40$ km/s and 70 km/s.

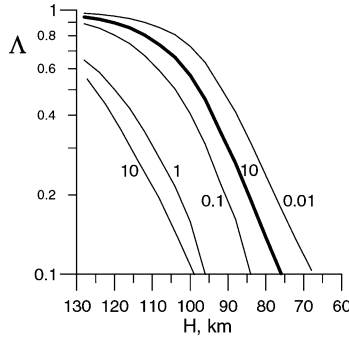


Figure 4. The heat transfer coefficient for different size (marked at the curves, cm) meteoroids versus altitude ($V \sim 70$ km/s – gray curves ; 10 km/s – black curve).

Boyd (2000) considered the rarefied flow around a Leonid meteoroid with a simplified ablation model by DSMC. He has demonstrated the critical influence of ablation on formation of a long hot meteor wake. The size of the hot meteor wake essentially increases if the ablation is taken into account. His modeling confirmed the formation of a vapor cloud around the body and that the meteor wake is the main source of radiation.

Baker et al. (2001) determined heat transfer coefficient Λ for a number of velocities ($V = 30, 50, 70$ km/s) and two meteoroid sizes ($R = 1, 8$ cm) and wide range of Knudsen parameter ($Kn \sim 0.44\text{--}175$) using DSMC. Their modeling confirmed the formation of the cloud of ablation products with density exceeding the density of surrounding atmosphere by several orders of magnitude. The efficiency of heat transfer essentially decreases in the presence of ablation material in comparison with free-molecule value ($\Lambda = 1$). They also suggested the extrapolation formulae for wider range of parameters (R, V, Kn) and confirmed its applicability. The values of heat transfer coefficient calculated based on their results are given in Figure 4. The heat transfer coefficient decreases with altitude decreasing and velocity increasing are in agreement with estimates given above. For 0.1 cm body at 90 km altitude the heat transfer coefficient decreases by 5 times in comparison with free molecule value for Leonids meteor velocity.

7. Continuous Flow

Meteor physics equations being applied to observational data collected by bolide observational networks permit a determination of the ablation coefficient $\sigma = \Lambda / 2QC_D$ and shape-density coefficient $K = C_D A \rho^{-2/3}$ average along trajectory (Pecina and Ceplecha, 1983; Ceplecha et al., 1993, 1998; Bellot Rubio et al., 2002) or varying along it (Ceplecha et al., 2000).

For fragile bolides (type III, attributed as cometary origin) the ablation coefficient is estimated as $\sigma = 0.1\text{--}0.2 \text{ s}^2/\text{km}^2$; for carbonaceous chondrites (type II) $\sigma = 0.042 \text{ s}^2/\text{km}^2$ and for ordinary chondrites $\sigma = 0.014 \text{ s}^2/\text{km}^2$ (Ceplecha et al., 1998). Ablation coefficient determined from observational data also includes the continuous fragmentation.

The heat transfer in the continuous flow consists of both convection and radiative transfer. The shock wave radiation and vapor radiation contribute to the ablation of the meteoroid. Different estimates of the convective and radiative parts of heat transfer coefficient Λ are used by different authors (Allen et al., 1963; ReVelle, 1979; Baldwin and Sheaffer, 1971; Stulov, 1997).

For three meteorites producing bolides ReVelle (1979) estimated the ablation coefficient as about $\sigma \sim 0.001\text{--}0.07 \text{ s}^2/\text{km}^2$. The ablation coefficient obtained in the numerical model by Golub' et al. (1996) is about $\sigma \sim 0.001\text{--}0.024 \text{ s}^2/\text{km}^2$ (for type I bodies). Theoretical estimates do not include any kind of fragmentation into the ablation coefficient.

Meteor equations are often used for large meteoroid entries in order to determine the energy release and to reproduce the dynamics and light curves of various bolides. The usual equations are often supplemented by different fragmentation models, because fragmentation is very important in the large meteoroid dynamics (Baldwin and Sheaffer, 1971; ReVelle, 1979, 1980, 2002; Borovička et al., 1998a, b; ReVelle and Ceplecha, 2002 and others).

Solution of the standard meteor equations requires knowledge of the ablation coefficient, luminous efficiency, etc. Values of coefficients extracted from observations or from theoretical modeling are used. There are a number of numerical models, which allow the determination of these values. These models are often one-dimensional (Biberman et al., 1980; Golub', 1996; Stulov, 1997).

The ablating piston model (Golub' et al., 1996, 1997) is a 1D self-consistent model of the meteoroid in the continuous flow regime. It is based on analogy between 1D nonstationary motion of a cylindrical piston and 2D quasistationary flow around the body. Meteoroid ablation and radiative transfer (in the vapor and in the air) are taken into account. A strict boundary between vapor and air is assumed (no mixing).

This model allows determining heat transfer coefficient, mass losses, thermodynamical parameters around the meteor head and in the nearby wake and the spectrum of bolide radiation. This spectrum is of a continuum type with superimposed lines; the role of the continuum increases with increasing meteoroid size and decreasing altitude. That is the reason why the continuum is negligible in fainter meteors.

The distribution of the brightness temperature (in the observational passband), the maximum temperature of the air and of the vapor are given on Figure 5a. Brightness temperature follows the vapor temperature and is substantially lower than T_{air} . The model predicts that a large fraction of

Nevertheless, these papers presented the first detailed comparison of a purely theoretical radiative-hydrodynamic spectral model and an observed spectrum of a bolide. Consistent description of the Benešov bolide, including its mass, dynamics, fragmentation and radiation was obtained (Borovička et al., 1998a, b).

Two- and three-dimensional models are able to describe directly the flow around the meteoroid. Great progress in the development of 2D–3D models occurred due to the fall of SL-9 comet. Published models allow to explain deformation, deceleration and light impulse from bolide (Ahrens et al., 1994; Boslough et al., 1994; Svetsov et al., 1995; Nemtchinov et al., 1997b and others).

Nevertheless, the modeling of meteoroid–atmosphere interaction in continuous flow is not complete. The 2D–3D modeling often does not properly take into account the ablation; radiative transfer is considered mainly under assumption of thermal conductivity, but that is satisfied only for relatively large bodies (optically thick).

The motion of two identical fragments through the atmosphere was modeled by (Artemieva and Shuvalov, 2001) in 3D simulations. Their approach took into account ablation and simplified model of radiation transfer (4 groups and 3 main directions). Motion of the chondritic body with size $R \sim 1$ m and velocity 20 km/s was considered at two altitudes of flight (50 and 70 km). The temperature of shocked air reached 2 eV, the temperature of vapor has the maximal values of about 0.7–0.8 eV at the boundary with the air. The temperatures in the near-wake are lower (about 0.3–0.4 eV). Ablated vapor screens the surface of the body, the heat transfer coefficient is estimated to be $\Lambda \sim 0.056$, $0.04(\sigma \sim 0.01 \text{ s}^2/\text{km}^2)$ and this agrees with earlier estimates (Biberman et al., 1980; Stulov, 1997). Results of this paper may be applied directly to chondritic meteoroids and as estimates to the meteoroids with relatively close composition. The volatiles-rich material should be considered separately.

Instabilities may also play a role in the interaction of large meteoroid with the atmosphere. Recently entry of cometary strength-less meteoroid ($R = 30$ m, $V = 30$ km/s) was considered by Shuvalov and Artemieva, (2002). Inclusion of the radiative transfer (in thermal conductivity assumption) considerably diminishes the near-wake temperatures; increases the wake radius and causes the energy redistribution in the near-wake in comparison with pure gasdynamic calculations (Figure 6). Ablation being taken into account causes the increase of effective meteoroid size and the size of the wake. The wake core with vapor is colder than outer layers (Figure 6). The temperature of the air reaches $T_{\text{air}} \sim 1\text{--}4$ eV, whereas the vapor is colder $T_{\text{vap}} \sim 0.4\text{--}0.8$ eV. During the further flight the vapor–air boundary is disturbed due to development of Rayleigh–Taylor, Kelvin–Helmholtz instabilities.

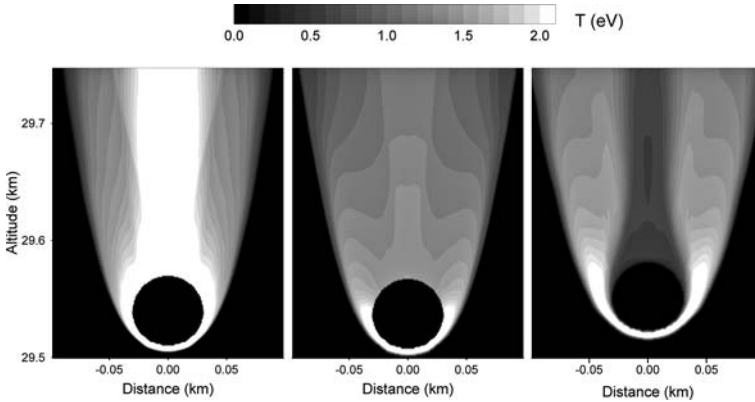


Figure 6. Temperature distribution obtained in pure gasdynamic run(left panel); in the run with radiative transfer (middle) and with radiation and ablation (right) (image due to courtesy Dr. Shuvalov).

Shuvalov and Artemieva, (2002) distinguish two main stages in meteoroid evolution. During the first stage the meteoroid is deformed, flattened and fragmented into a nonuniform debris jet. Near-wake and debris jet itself consists of highly mixed vapor and shock compressed air. At the second stage the elongated debris jet is decelerated and most of the energy is released. Hot air and vapor accelerate upward and creates a ballistic plume. Ablation rate (and heat transfer coefficient Λ) experiences oscillation due to vapor absorption and variation of vapor layer thickness.

8. Conclusions

The local flow regime realized around the falling body determines the heat transfer and mass loss processes. Ablation is dependent on size (or mass), velocity, altitude of flight and meteoroid properties. We have tried to review existing ablation models in different flow regimes and to note model boundaries. Here it seems useful to mention main questions, which are still open.

In free molecule regime the ablation rate is known, but the determination of luminous and ionizing efficiencies; place of differential ablation; state of ablated material and spectra formation are still unclear. Also the importance of fragmentation, which is closely connected with the question about meteoroid structure, needs to be clarified.

Meteoroid modeling in the transition regime progressed significantly during last years. DSMC and hybrid modeling, which combined both MC and gasdynamic approaches, are good tools here. But only first estimates of parameters in ablated material were done up to now.

There are no totally self-consistent 2D–3D model with radiation and ablation for whole range of sizes, velocities and altitudes of flight, and meteoroid material in the continuous regime. Detailed comparison of observational and model results is done for limited number of events due both to incomplete observational data and modeling problems.

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INTERPLANETARY DUST AND CARBONACEOUS METEORITES: CONSTRAINTS ON POROSITY, MINERALOGY AND CHEMISTRY OF METEORS FROM RUBBLE-PILE PLANETESIMALS

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Abstract. This paper discusses measured textures, porosity, chemical compositions and the minerals of interplanetary dust and meteorites from primitive planetesimals and how this information can be used to explain some of the observed physical and chemical properties of meteor phenomena.

Keywords: Asteroids, carbonaceous chondrites, chemistry, comets, interplanetary dust particles, meteors, mineralogy, porosity, rubble-pile planetesimals, structure

1. Introduction

1.1. GOAL

I will discuss interplanetary dust particles (IDPs) and meteorites that are the remains of meteoroids from the infrared (IR) *C* (carbonaceous chondrite), *P* (primitive; very carbonaceous chondrite) and *D* (dark; ultra carbonaceous chondrite) classes of small solar system bodies, e.g. comet nuclei, a fraction of Near-Earth Asteroids, and outer belt asteroids. Since this debris was collected it can be analyzed in our laboratories for its physical, chemical and mineralogical properties (e.g., Flynn, 1994a). Except in the rare case of meteorite recovery after an observed bolide, the meteor phase in between meteoroid entry and debris collection can only be assessed remotely. However, meteor streams have a direct source relationship and in such cases meteors become probes of source composition, processing (evolution) and on-orbit dust aging as a function of dust release time. My thesis is that there has to be a connection between the physical expression of a meteor and the meteoroid's properties. What might be the exact connection(s) will be a matter of emerging interdisciplinary research. I will highlight a few cases to show how the studies of collected extraterrestrial debris could be used to constrain meteor observations.

1.2. RUBBLE PILES: COMETS AND PRIMITIVE ASTEROIDS

Active comets are a major source for meteor streams but near-Earth asteroids are also linked to meteor streams, including the Taurid complex. The sharp distinction between comets and asteroids based on orbital parameters, the ability to develop a coma, and their IR reflectance properties, is no longer an “either-or” issue (Rietmeijer, 2000a). The notion that all comets are dirty snowballs was revisited in the wake of the comet Halley missions because a rubble pile model appeared to better explain the observations (Gombosi and Houpis, 1986; Weissman, 1986; Stöffler, 1989). In a rubble pile the centimeter to sub-meter pebbles, boulders and small planetesimals are held together gravitationally or by “Whipple-glue” that could be dirty-ice to icy-dirt. A rubble pile provides a range of environments that, short of a comet nucleus-sampling mission (Rietmeijer, 2002a), are only accessible as extraterrestrial debris delivered naturally to the Earth, e.g. two cm-sized Perseid meteoroids (Borovička and Betlem, 1997) that could be rubble pile pebbles. Meteoroid interactions with Earth’s atmosphere introduce a bias in the collectable debris in the sub-cm to centimeter range and up to the smallest meteorites that are often fragments of larger meteoroids (Jenniskens et al., 1994; Ceplecha et al., 1998; Borovička and Kalenda, 2003).

What samples might we expect to collect from rubble piles comets or *C*, *P* and *D* asteroids? It is unlikely, even undesirable, that we will receive intact samples of the 100’s of meters and larger rubble pile units, but we could settle for fragments. Such meteorites might include pebbles and (smaller) boulders:

1. Anhydrous proto-CI material (Rietmeijer and Nuth, 2000) that was not yet found among the collected meteorites, and
2. Hydrated (proto-CI) debris that might resemble the hydrated fine-grained CI1 (formerly CI) and CI2 (Tagish Lake) carbonaceous chondrites and perhaps even the fine-grained matrix of CM chondrites.

I would not expect chondrules and refractory inclusions (cf. Brearley and Jones, 1998) to be present in a rubble-pile body because, in our current understanding of solar system formation, it would imply efficient, radially outwards, chondrule transport. The Tagish Lake meteorite is a (IR) *D*-class object with a few chondrules and refractory debris but with smectite rather than CI-and CM-serpentine layer silicates (Brown et al., 2000), which make it a very interesting primitive stone. The rubble-pile pebbles might offer a dichotomy of fine-grained planetesimal aggregate debris and compacted matter that evolved *in situ* by the hydration of dust aggregates embedded in “Whipple-glue” of dirty-ice during gradual loss of ice and after complete ice

melting. Most debris ejected in jets during perihelion appears to consist of porous fragments that will break up when moving away from the active comet nucleus as seen at comets Halley (Jessberger et al., 2001) and Wild-2 (Tuzzolino et al., 2004). Some of the collected aggregate IDPs and cluster IDPs could be such ejected dust.

The hypothesis of hierarchical dust accretion describes how solar nebula dust aggregation and evolution began with agglomerates of circumstellar dust that led by a stepwise, fractal accretion process to the formation of porous aggregate IDPs to cluster IDPs and sub-millimeter and larger aggregates (Rietmeijer, 2002b, c). I consider the matrix of CI1, CI2 and CM meteorites to be huge accumulations of dust-clusters and, as such, I see a continuum of properties that could be helpful in assessing the physical interactions of mm- and cm-sized meteoroids with the Earth's atmosphere. Hydration of such aggregates at any stage of hierarchical dust accretion and evolution will lead to compaction when ices are lost after which hydration could redistribute chemical elements, for example by leaching from the original accreted dust and deposition in veins as seen in CI meteorites (cf. review by Brearley and Jones, 1988). The hierarchical dust accretion hypothesis describes systematic changes in dust size and composition that results in the formation of 'chemically complex' amorphous dust and new minerals (Rietmeijer, 2002b).

2. Astrominerals and Planetesimals

The original solar nebula dust, prior to accretion and processing, would probably show vestiges of formation by vapor phase condensation. It would also include dust that was formed and processed in the interstellar medium and in circumstellar or other astrophysical environments. Or, looking at it differently, Astrominerals such as those that were seen by the Infrared Space Observatory (*ISO*) show what kinds of dust were present in the solar nebula. Dust that now forms the major mineral constituents of aggregate and cluster IDPs. The major *ISO* dust (Bouwman et al., 2001; Keller et al., 2002; Molster and Waters, 2003) is listed and examples found in aggregate IDPs are shown (Figures 1 and 2):

1. Crystalline silicates: forsterite (Mg_2SiO_4) (Figure 1a); enstatite ($\text{Mg}_2\text{Si}_2\text{O}_6$) (Figure 1b); silica (SiO_2) (Figure 1c); diopside ($\text{MgCaSi}_2\text{O}_6$) (Figure 1d),
2. Amorphous Mg,Fe-silicates (Figure 2a), and
3. Fe-sulfide (pyrrhotite, Fe_7S_8) (Figure 2b).

When trying to interpret the chemistry of meteors from primitive, small bodies (rubble-piles) these minerals should be considered as sources of the observed elements and the relative chemical abundances.

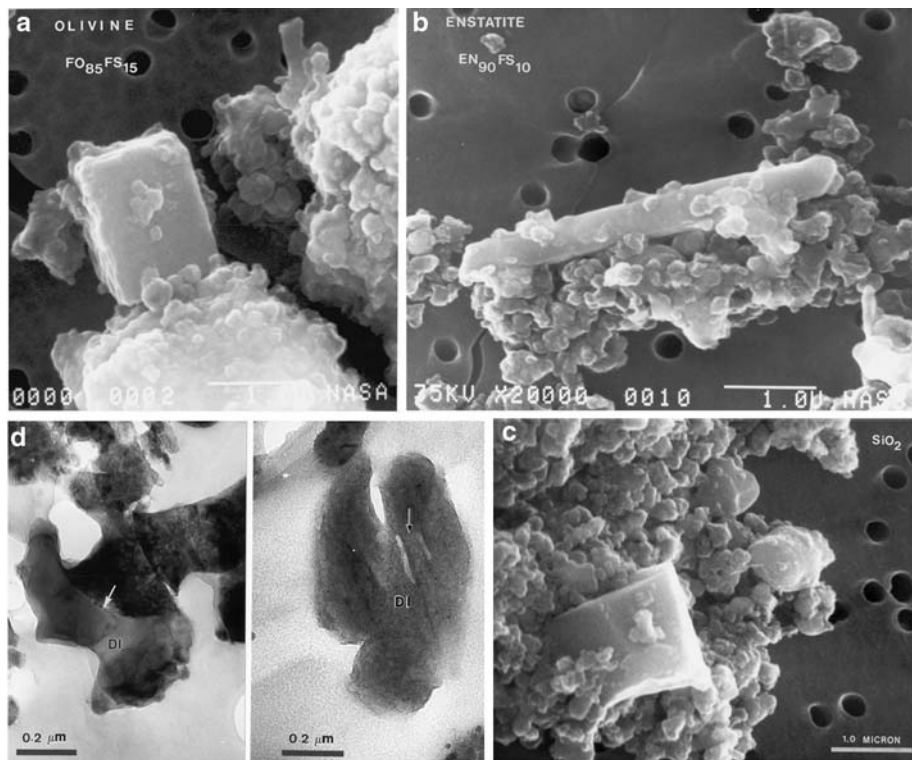


Figure 1. Scanning electron microscope (SEM) images of silicate minerals in the accretion matrix of the aggregate IDP W7010*A2. Shown in a clockwise direction from the top-left are (a) a single-crystal Mg-rich olivine (composition shown), (b) an elongated, whisker-like, enstatite single-crystal (composition shown), and (c) a silica single-crystal (probably tridymite) and (d) a composite of transmission electron microscope (TEM) images showing an ultrathin section of an anhedral diopside crystal grain (left) and amorphized diopside due to irradiation exposure in space (right) in aggregate IDP L2011K7. The background in the SEM images shows the nuclepore support filter; in the TEM images it shows the epoxy wherein the IDP was embedded for TEM analysis. *Sources:* (1a) Rietmeijer (1989), unpublished data; (1b) Rietmeijer (1992); (1c) reproduced from Rietmeijer (2002b); (1d) reproduced from Rietmeijer (1999a).

3. Interplanetary Dust Particles (IDPs)

For the sake of brevity, I will heavily rely on the review papers by Rietmeijer (1998, 2002b) wherein all original references and observations are listed. At the first level of classification (Figure 3) we find (1) chondritic IDPs and (2) non-chondritic IDPs. Non-chondritic IDPs are

1. Massive silicate particles (Figure 4a), such as Mg,Fe-olivines and Mg,Fe $\pm$ Ca-pyroxenes,
2. Massive sulfide particles [pyrrhotite; pentlandite (FeNi)₉S₈] (Figure 4b), and

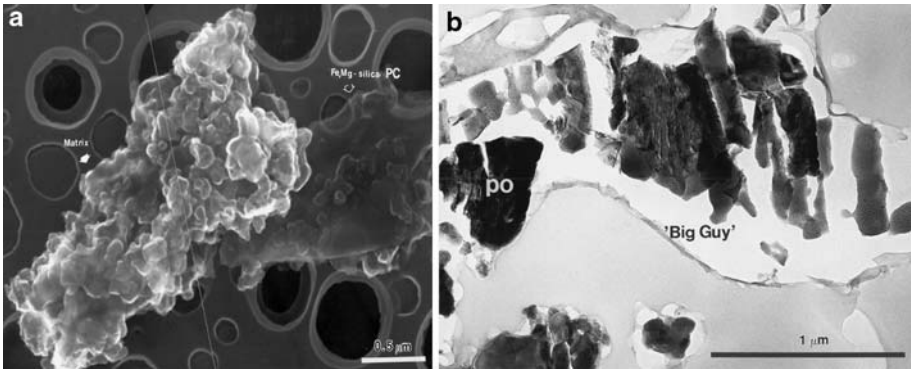


Figure 2. (a) SEM image showing an amorphous, (Fe,Mg)-bearing high-Si, aluminosilica grain attached to a matrix aggregate in chondritic porous aggregate IDP W7029*A with supported on a nucleopore filter (left), and (b) TEM image of an ultrathin section of a large amorphous, Fe,Mg-bearing high-Al, aluminosilica grain (Big Guy) and a pyrrhotite (po) in the matrix of highly porous aggregate IDP L2011A9 (right). The light gray background is the embedding epoxy used to prepare the section. White areas show where material was lost during ultramicrotome sectioning. This is a common artifact that might be related to atmospheric entry flash heating causing brittleness in micron-sized amorphous grains, silicates and sulfides. Sources: (2a) reproduced from Rietmeijer (1992); (2b) modified after Rietmeijer (1994, 1998).

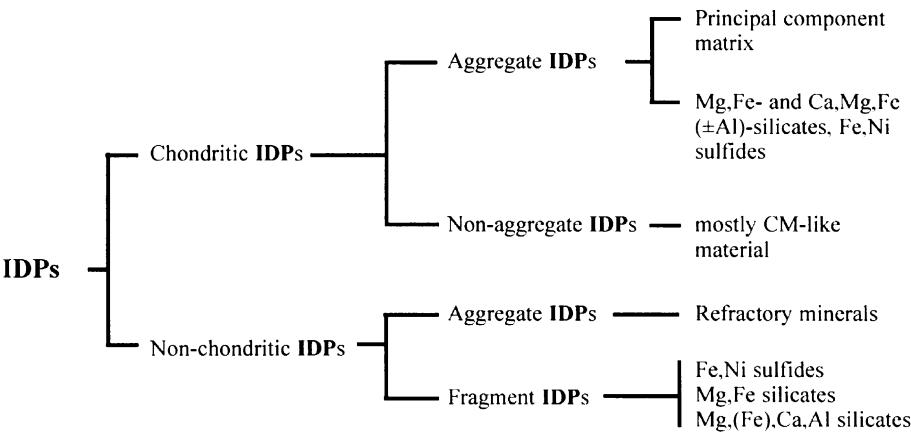


Figure 3. Chemical and morphological classification of IDPs collected in the Earth's lower stratosphere (columns 2 and 3) and mineralogical identification of aggregates and fragments (column 4) (modified after Rietmeijer, 2000b, 2002b).

3. Refractory (Ca,Al,Mg ± Ti) aggregates.

Chondritic and non-chondritic IDPs on the collectors are mostly ~10–15 μm; rare up to ~50 μm. They are collected on inertial-impact, flat-plate collectors mounted underneath the wings of high-flying aircraft in the

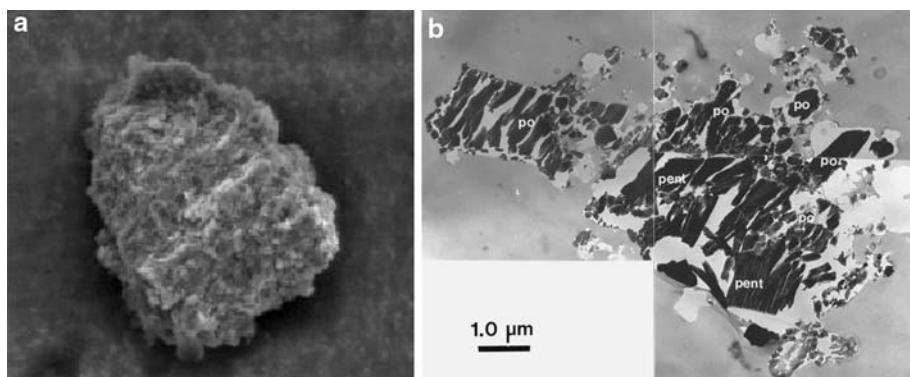


Figure 4. (a) SEM image of non-chondritic Mg,Fe-silicate IDP L2047D23 ($42 \times 34 \mu\text{m}$) (left) and (b) TEM image of an ultrathin section of massive sulfide IDP L2005E40 that is an intergrowth of pyrrhotite (po) and pentlandite (pent). The white areas show indicate where sample material was lost during ultathin sample preparation. It is a common feature seen in these sulfide IDPs. A narrow Fe-oxide rim is visible on pyrrhotite on the right; a molten patch of aggregate-IDP-like material (light-gray lobe in the lower right). The embedding epoxy shows as the dark gray background. *Sources:* (4a) NASA Cosmic Dust Catalog, 17, 2002, CD-ROM; (4b) reproduced from Rietmeijer (2004).

lower stratosphere at $\sim 17\text{--}19$ km altitudes (Zolensky et al., 1994). It is assumed that size “as-collected” is the particle size prior to collection. Many non-chondritic IDPs have patches of aggregate IDP material at the surface indicating they were structurally are related to chondritic aggregate IDPs. In fact, high concentrations of $\sim 15 \mu\text{m}$ size dust on the collectors are interpreted as cluster IDPs (~ 100 to $\sim 500 \mu\text{m}$) that broke apart during impact (Flynn, 1994b; Thomas et al., 1995, Rietmeijer 1997, 2004).

Chondritic IDPs form (1) aggregate IDPs (Figure 5a) and (2) non-aggregate IDPs without any traces of a pre-existing aggregate texture (Figure 5b). The petrological properties of the latter resemble the fine-grained matrix of CI1, CI2, CR and CM chondrites; iron oxides are common in IDPs and often form a partial or complete rim at the surface due to atmospheric entry heating (see review by Rietmeijer, 1998).

4. IDPs and Meteorites Linked

4.1. HIERARCHICAL DUST ACCRETION AND ‘HUMPED’ LIGHT CURVES

The smallest presolar and nebular dusts that survived, principal components (PCs), are ~ 90 nm up to $\sim 1,000$ nm in size and form the matrix in aggregate IDPs (Figure 5a):

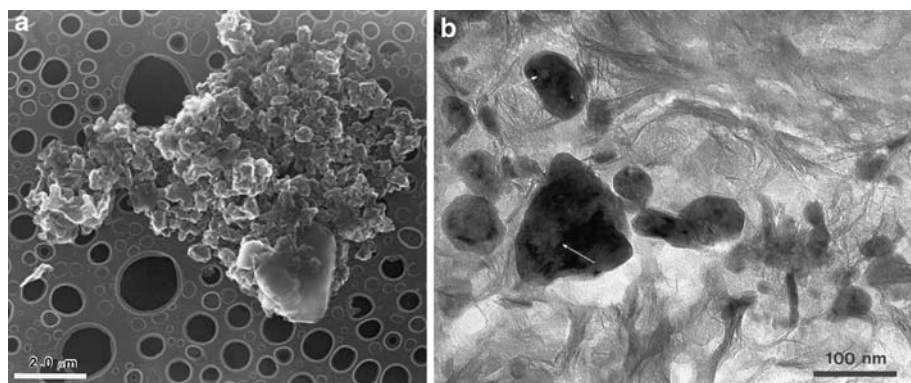


Figure 5. (a) SEM image of the highly porous (fluffy) chondritic aggregate IDP W7010*A2 with a typical matrix of principal components (left). The background is a nuclepore filter for support during electron microscope analysis. What are now holes in the structure were most probably originally filled with ice, and (b) TEM image of an ultrathin section of chondritic non-aggregate IDP L2011O3 that resembles CM chondrite matrix because of its typical amorphous ferromagnesian silica matrix with sinuous proto-phylosilicates (light to dark gray) and embedded rounded sulfide grains (black) with tiny vesicles (white arrows) from S-loss during atmospheric entry or irradiation in interplanetary space prior to accretion into the matrix (right). *Sources:* (5a) reproduced from Rietmeijer (1992); (5b) reproduced from Rietmeijer (1996).

1. Carbonaceous PCs of refractory hydrocarbons (unspecified), PAHs, organic carbons, amorphous carbons, poorly graphitized and pre-graphitic turbostratic carbons,
2. Carbon-bearing ferromagnesian silica, or 'mixed', PCs of ultrafine (< 50 nm) silicates, Fe,Ni-sulfides, Fe-oxides in a carbonaceous matrix,
3. Amorphous Mg-rich ferromagnesian silica PCs ($\pm$ minor Al, Ca, Na) with a metastable eutectic $(\text{Mg,Fe})_6\text{Si}_8\text{O}_{22}$ (smectite) dehydroxylate bulk composition,
4. Amorphous Fe-rich ferromagnesian silica PCs with a metastable eutectic $(\text{Mg,Fe})_3\text{Si}_2\text{O}_7$ (serpentine) dehydroxylate bulk composition, and
5. GEMS [glass with embedded (iron–nickel) metal and sulfides; Bradley, 1994], although these objects may contain some (unspecified) amount of carbonaceous materials (Bradley et al., 1999).

The IDP classification scheme (Figure 3) shows that the porous matrix incorporates ~ 5 μm silicates (Figure 1), sulfides (Figure 2b) and amorphous aluminosilica grains (Figure 2a), and refractory dust that, while mixed in randomly variable proportions, make up the typical porous (10–15 μm) aggregate IDPs. The hierarchical dust accretion hypothesis predicts that the same constituents grow incrementally, *viz.* those shown in Figure 4, and that they accrete into incrementally larger aggregates. That is, an earlier-formed

aggregate IDP co-accreted with ~ 10 to $15\ \mu\text{m}$ -sized silicate and sulfide dust to form cluster IDPs up to $\sim 500\ \mu\text{m}$. This stepwise accretion process in principle could continue to form millimeter and up aggregates that could no longer survive atmospheric entry (Rietmeijer and Nuth, 2004).

Humped meteor light curves provide evidence that such large aggregates exist as composite meteoroids with a dustball component and a massive grain. The light curve of one Leonid storm meteor revealed two components of $(2.4\text{--}2.5) \times 10^{-4}\ \text{g}$ each (Murray et al., 2000). Making reasonable density assumptions, this meteoroid had a $\sim 575\ \mu\text{m}$ -sized dustball ($1\ \text{g/cm}^3$) component and a massive component that, when an Mg-rich silicate ($3.3\ \text{g/cm}^3$) was $\sim 525\ \mu\text{m}$ in size, or $\sim 450\ \mu\text{m}$ in case it was a Fe-sulfide (pyrrhotite; $4.6\ \text{g/cm}^3$) grain. This meteoroid was probably a giant cluster. The silicate or sulfide component could be either a single-crystal grain or a compact cluster of smaller silicate or sulfide grains. The hierarchical dust accretion hypothesis does not exclude aggregation of non-chondritic dust into compact mono- or polyphase silicate or sulfide clusters. Compact, non-chondritic, mostly Mg,Fe meteoroids on cometary orbits, *incl.* debris with an Oort cloud origin, exist (Borovička et al., 2002).

These compact meteors are Na-free which should not be a surprise when they consisted of silicate dust that, insofar it is present among the collected non-chondritic IDPs, does not contain Na-minerals. This group of meteors includes the Karlštejn fireball on a retrograde, high-inclination orbit with an estimated $\sim 3.5\ \text{g/cm}^3$ (but $> 2\ \text{g/cm}^3$) density (Spurný and Borovička, 1999). The photometric mass range (Borovička et al., 2002), indicates a size range of $\sim 800\ \mu\text{m}$ to $\sim 25\ \text{mm}$, assuming a silicate density. Even the smallest of these meteoroids are larger than many Mg-rich olivine grains in the matrix of CII and CM chondrites (Kerridge and MacDougall, 1976; Richardson and McSween, 1978). The hypothesis does not prohibit the formation of large refractory aggregates or large aggregates of almost exclusively silicates, or sulfides, or purely carbonaceous dust. In general accretion would produce mixed chondritic dust assemblages. The non-chondritic aggregates could reflect unusual dust concentrations as a function of time (turbulence) and location in the nebula.

The “non-chondritic” label for these Mg,Fe meteoroids was used to indicate their bulk composition. However, the laboratory analyses studies of collected IDPs (see Rietmeijer, 1998) show that aggregate IDPs can have a chondritic composition for most but not all of their rock-forming elements. The hypothesis of hierarchical dust accretion offers an explanation for this feature, including volatile elements such as Na. In a survey of meteor spectra and orbits Borovička et al. (2005) showed considerable non-chondritic element abundances in bulk composition or for specific elements in cometary and asteroidal meteoroids. Specifically with regard to highly variable Na-contents Borovička et al. (2005) these offered thermal desorption and on-

orbit aging (solar heating) as Na-loss processes. I note that the current chondritic Na value may be too low as inferred from the formation of a Na-tail of some comets (Rietmeijer, 1999b).

4.2. BULK SILICA CONTENT OF COMETARY METEOROIDS

The solar system abundances, also known as the CI abundances, of the elements are based on the measured abundances in the solar photosphere and CII carbonaceous chondrites (*a.o.* Anders and Grevesse, 1989). A CII meteorite is essentially a ‘chunk of clay’ after the complete hydration, which begs the question whether the original elements could have been redistributed. Ebihara et al. (1982) concluded that it was not a problem for trace elements. The situation might be different for major rock-forming elements. For example, Ca and S were dissolved (leached) and redistributed in small veins in CII meteorites. Laboratory hydration experiments showed that hydration would leach silica (SiO_2) from the precursor to be precipitated as pure silica pockets (Rietmeijer and Nuth, 2000). They submitted that the bulk anhydrous “proto-CI” composition contained more SiO_2 than CI meteorites. Recently, Borovička (2005) reported $>\text{CI}$ SiO_2 contents in Leonid and Perseid meteoroids. It suggests that anhydrous proto-CI material could be preserved in comet nuclei.

4.3. HYDRATION AND HYDROGEN IN METEORS

Dust accretion beyond the snowline in the solar nebula produced mixtures of dust and ice. Evidence for this is found in the surviving aggregate texture of porous aggregate IDPs that, once they had lost their ice after ejection from their parent body into space, then did not suffer physical collapse of the ‘empty’ pores. When dust-ice mixtures resided in a parent body wherein the temperature could rise above -50°C , hydrocryogenic alteration could initiate hydration of the anhydrous dust and form layer silicates and salts (carbonates; sulfates). Aqueous alteration became more efficient at temperatures (slightly) above 0°C and the empty pore spaces began to collapse resulting in low-porosity, partially to completely hydrated, aggregates. This scenario is supported by results of laboratory hydration experiments of condensed MgSiO silicate smokes that showed how abundant nanometer layer silicates formed readily at low temperatures in metastable magnesiosilica dust with distinct serpentine- and smectite-dehydroxylate compositions (Rietmeijer et al., 2004). The experiments showed that an initial porous texture gradually collapses with only the smallest pores surviving noting that complete MgSiO hydration was not achieved. Extrapolated,

however tentatively, the H/Fe ratios from these experiments show that the measured H/Fe = 38.9 for comet Halley (Jessberger et al., 1988) and H/Fe = 14 ± 5 for a 2001 Leonid Storm meteor (Jenniskens and Mandell, 2004) indicate < 25% hydration for dust in comets Halley and Temple-Tuttle.

In summary, stepwise accretion of anhydrous dust will lead to continuously larger, porous aggregates. Aggregates beyond the snowline contained ice. Loss of ice by melting and resultant aqueous alteration produced increasingly lower porosity for increasingly hydrated aggregates. Hydration will be mostly limited to amorphous ferromagnesian silica and aluminosilica dust while crystalline dust, e.g. olivine, pyroxene and Fe(Ni)-sulfide, was not (yet) affected. Hydration is an efficient process to collapse porous aggregates in icy planetesimals. Compaction due to thermal processes or gravitationally will occur when internal thermal energy is generated by radiogenic decay or impacts in sufficiently massive parent bodies.

4.4. METEORITES AND CARBON METEORS

Lithification and its effects are imprinted on carbonaceous chondrite meteorites including the almost anhydrous CR, CO and CV carbonaceous chondrites (Table I) (cf. Brearley and Jones, 1998, for detailed meteorite descriptions). Perhaps there is an as yet unknown relationship among refractory aggregate IDPs (Zolensky, 1987) and the <1 mm to >1 cm refractory Ca,Al-rich inclusions in meteorites (Table I). Their high concentrations in CO and CV meteorites could suggest accretion regions that were different than those for CR, CI (renamed CII) meteorites. In this argument the position of highly aqueously altered CM chondrites is ambiguous. Still, there is a significant similarity among the constituents of dust aggregates and those in the carbonaceous meteorites. Chondrules are unique to these meteorites (Table I). The approximately chondritic chondrule compositions

TABLE I

Approximate proportions (vol.%) of components in various carbonaceous chondrite meteorites (data from Brearley and Jones, 1998)

Meteorite groups	Matrix	Chondrules [diameter, mm]	Refractory Ca,Al-rich inclusions	Fe,Ni-metal grains
CI	> 99	< < 1	< < 1	0
CM	70	20 [0.3]	5	0.1
CR	30–50	50–60 [0.7]	0.5	5–8
CO	34	48 [0.15]	13	1–5
CV	40	45 [1.0]	10	0–5

resemble the bulk meteorite composition. Differentiated meteorites include achondrites (mostly igneous and basaltic rocks), stony irons and irons. These meteorites (Table I) represent ~5.5% of all meteorite ‘finds’ and ‘falls’ and collectively are ~9% of the total (collected) meteorite mass (cf. Rietmeijer, 2002d).

There is a perhaps significant difference albeit not inconsistent with an accretionary continuum in the properties of IDPs and carbonaceous chondrites, e.g. in their volatile element make-up and contents. The light elements in comet Halley are sequestered in CHON particles with a bulk formula, $C_{100}H_{80}N_4S_2O_{20}$ (Kissel and Krueger, 1987) with a CI-normalized carbon content of 11.6 (Jessberger et al., 1988). Chondritic aggregate IDPs are by-and-large carbon-rich dust with an average bulk carbon content ~2 to 3 times the CI abundance. The carbon contents among individual aggregate IDPs range from ~1 to 47 element wt% with the highest value corresponding to ~13 times the CI abundance (Thomas et al., 1996). The PCs (Section 4.1) show that carbon is mostly locked in the carbonaceous PCs with (unknown) lesser amounts in “mixed” PCs and certain GEMS. Various among the accreting PCs alone could account for the range of bulk carbon content of anhydrous and partially hydrated aggregates IDPs. Assuming such IDPs once made up matrix of CI1, CI2 and CM meteorites, the increasingly higher intensity of aqueous alteration in these meteorites would contributed to loss of CHON-like material, if not modified it. This scenario does not exclude that these meteorites could not have accreted other organic materials that were unique to their accretion regions. Either way, meteorite matrix is not carbon-free but dominated by amorphous ‘silicate’ material and silicate minerals (e.g. Brearley, 1995, Brearley and Printz, 1992). The C-rich aggregate IDPs often show large, contiguous areas of carbon material enclosing silicate materials and sulfides (Thomas et al., 1993; Keller et al., 2004). This texture is often interpreted as being a primary one but quite possibly it could be a secondary texture that formed during atmospheric entry flash heating with concomitant carbon loss. The ‘primary’ origin might give a false impression of CHON-like material being the ‘glue’ holding aggregate dust together. Such ‘glue’ seems inconsistent with the observed fragmentation of aggregates ejected from comets Halley and Wild-2 (Tuzzolino et al., 2004). Using the conventional atmospheric entry heating approach whereby surface atoms are released by thermal processes, high (above ~130 km) meteor ablation altitudes are linked to the presence of volatile species (Spurný; et al., 2000) that could be CHON-like material or other indigenous volatile species (Rietmeijer, 2000a, b, 2002c). At these high latitudes this thermal process may not be efficient but physical sputtering processes could be for high altitude meteors (Hill et al., 2005).

One of the implications of linking meteor data to the know properties of IDPs and meteorites would be a correlation between meteor ablation altitude

and bulk carbon content and degree of hydration of incoming meteoroids, that is, of course everything else being invariable in terms of velocity and mass, among others. This predicted correlation might be testable for shower meteors.

4.5. DENSITY AND POROSITY

The measured density and porosity of CII ($\sim 1.6 \text{ g/cm}^3$), CM ($\sim 2.2 \text{ g/cm}^3$) and CO/CV ($\sim 3.5 \text{ g/cm}^3$) chondrites show a continuous trend with bulk porosity of these meteorites decreasing from 35 to $\sim 10\%$ (Rietmeijer and Nuth, 2000 with a listing of the original sources). This correlation suggests increasing compaction as a function of hydration (CII; CM) and thermal alteration (CO; CV). Such correlated data for individual IDPs are unavailable. Porosity measurements for two highly porous aggregate IDPs offer the best approximation at this time: (1) porosity 95%; density 0.1 g/cm^3 and (2) porosity 75%; density 0.7 g/cm^3 (see Table 10 in Rietmeijer, 1998). These values support initial compaction during early accretion. Calculated highly-porous IDP densities (Rietmeijer, 1993) are comparable to those for ‘regular cometary material’ (0.75 g/cm^3) and ‘soft cometary material of short-period Giacobini-Zinner type comets’ (0.27 g/cm^3) of meteor classification (cf. Ceplecha et al., 1998). The pre-atmospheric porosity of the physically ‘weak’ Tagish Lake meteor was 40–60% classifies it between a ‘carbonaceous chondrite’ (Type II) and ‘comet-like’ (Type III) fireball (Brown et al., 2001) or between the most porous IDPs and CI chondrites.

Density data are available for many IDPs. They show two groups, but only for discussion purposes, rather than at this time claiming a real subdivision. When dust accretion was the only process controlling fractal aggregate formation, one expects a regular non-linear correlation between aggregate size and density (Figure 6, dotted line). The linear correlation (Figure 6; open squares) suggests that other processes, e.g. (partial) hydration, left an imprint on these particles. Complete hydration (total collapse) would increase aggregate density to $\sim 2.6 \text{ g/cm}^3$ and higher for IDPs with contained silicate minerals, Fe-sulfides, or both. Thermal processing in a parent body or during atmospheric entry could also increase aggregate density. The dashed line (Figure 6) is realistic since all IDPs experience some degree of flash heating. The two highly porous aggregate IDPs plot at its extension to low density. Calculating the diameter of these two IDPs (assuming 1.7 g/cm^3 density) yields $\sim 25 \mu\text{m}$ that is similar to the largest particle on the solid line. It highlights the size bias in collected IDPs due to atmospheric entry survival. The linear correlation line includes some heated aggregate IDPs with ~ 15 to $\sim 50\%$ porosity (Table 10 in Rietmeijer 1998). The denser chondritic IDPs (Figure 6; open diamonds) include CF IDPs ($0.4\text{--}3.4 \text{ g/cm}^3$) and partially hydrated aggregate IDPs (5–20% porosity)

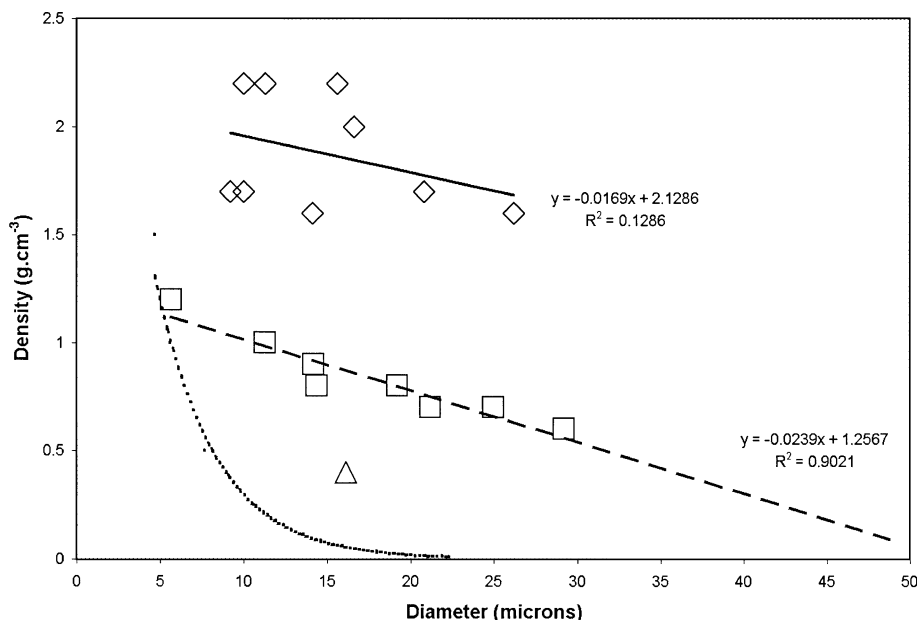


Figure 6. Measured density (g/cm^3) and size (μm) of chondritic IDPs (Table 11 in Rietmeijer, (1998), with sources of the original data) defining two correlation groups (squares; diamonds) presented as linear correlations (dashed and solid lines). One IDP (triangle) is probably a slightly processed, highly porous aggregate. The dotted line defines a lower limit for aggregate size and density.

[the CF label, chondritic filled, was used as a distinction to from highly porous aggregate IDPs based on morphology alone; Zolensky et al., 1994]. A study of 81 chondritic IDPs (5–15 μm) showed densities ranging from 0.3 to 4.3 g/cm^3 (mean density 2 g/cm^3 ; 1.8 g/cm^3 modal density (Love et al., 1994). With hierarchical dust accretion from aggregate IDPs to sub-millimeter clusters, the bulk density gradually increases as large silicates and sulfides become incorporated. The highest possible meteoroid density (when not a differentiated, stony-iron or iron meteoroid) is 4.6 g/cm^3 for a massive sulfide IDP.

5. Case Studies

5.1. METEOR CHEMISTRY

Trigo-Rodriguez et al. (2003) determined the major element abundances in a sporadic meteor (SPO4; mass of 2 g) with a 57.1 km/s entry velocity placing it among high-velocity comets. This meteor reportedly had a very low Mg/Si ratio but almost CI-like Fe/Si ratio. Could its chemical composition, using the minerals found in aggregate dust, provide clues to SPO4's minerals? Its

Ca and Na might be allocated to Ca,Na-bearing aluminosilica grains (Figure 2a). The Mg,Fe-silicate (olivine; Ca-free/low-Ca pyroxene) compositions in chondritic IDPs range from $mg = 0.5\text{--}1.0$ with the majority $mg > 0.8$ (Zolensky and Barrett, 1994). The SPO4 bulk ratio $Mg/(Mg + Fe)$ (mg) = 0.4 could support Mg-rich pyroxene (> 0.8) plus Fe-sulfide, or more Fe-rich pyroxene, $mg < 0.8$, with a higher abundance of sulfides. Its mass suggests a compact particle that is consistent with the Ca and Na allocations to aluminosilica grains that are evolved dust as predicted by the hierarchical dust accretion hypothesis. When these initially amorphous grains had crystallized, SPO4 would contain compact patches of plagioclase ($CaAl_2Si_2O_8$), Al_2SiO_5 , and silica minerals. The amorphous or crystalline nature might affect the relative appearances of (Na,Ca) and Mg in a meteor light curve. This meteor was a, probably compact, aggregate of pyroxene, Fe-sulfide and (Ca,Na)-bearing aluminosilica dust grains. The example intends to show what could be possible when meteor data are reduced in a petrological manner that could ultimately provide a picture of physiochemical conditions in rubble-pile planetesimals.

5.2. CHEMICAL VARIATION AS A FUNCTION OF SIZE

The Perseids that appear to be more compact than Leonid meteors (Koten and Borovička, 2001) include some large (cm-size) meteors with a bulk chondritic composition that because of the high velocity and temperatures could efficiently ablate calcium, which is somewhat unusual (Borovička and Betlem, 1997). The physical interactions with the atmosphere for individual meteoroids of a shower should be similar so that chemical differences among these meteors would reflect a distinctive parent body property. Trigo-Rodriguez et al. (2003) reported chemical compositions for five Perseid meteors with a photographic mass ranging from 0.2 to 29 g. Meteors with the smallest mass (0.2–6 g) had sub-chondritic Ca/Si abundances while the PER4 meteor (29 g) contained significantly more calcium (Figure 7). The arrows originating from the most primitive solar system materials analyzed to date (open squares) define two tracks of dust evolution, viz. (1) anhydrous aggregate accretion (upper arrow) and (2) dust accretion and parent body hydration (lower arrow) (Figure 7). One arrow is drawn to the average composition of ‘chondritic smooth IDPs’ (Schramm et al., 1989) that are probably collapsed, hydrated aggregate IDPs. Hydration was hypothesized to decrease the Ca-content of originally anhydrous chondritic dust (Schramm et al., 1989) although another study reported no correlation between hydration and Ca depletion in particles with lower than chondritic Ca/Si abundances (Zolensky and Barrett, 1994). In other words, sub-chondritic Ca/Si appears to be an indigenous property

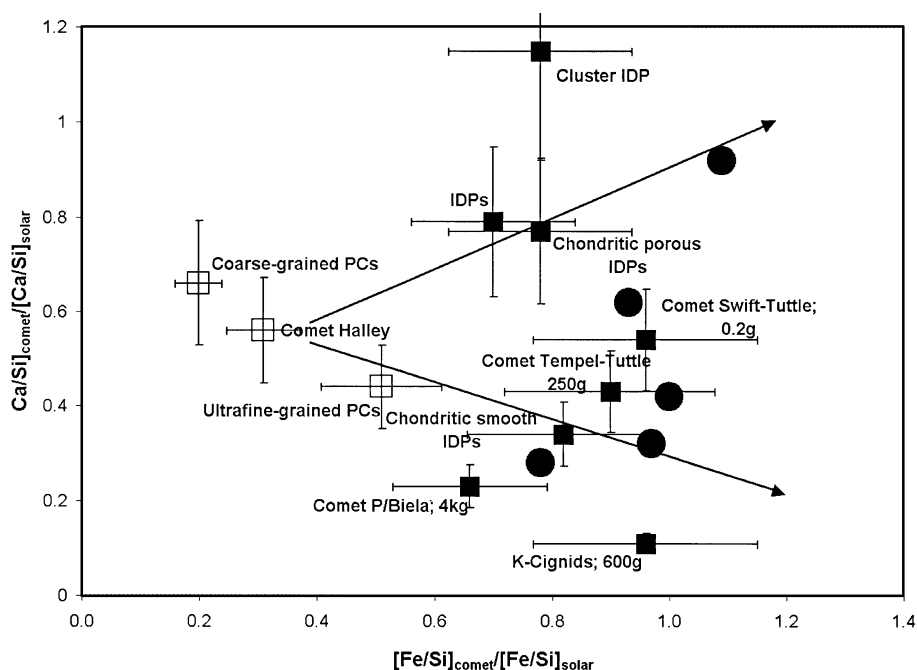


Figure 7. Fe and Ca ratios (Si and solar normalized) in ferromagnesian PCs (Rietmeijer, (2002b) and comet Halley dust (Jessberger et al., 1988) (open squares), in chondritic porous IDPs, chondritic smooth (i.e. collapsed aggregate) IDPs, cluster IDPs (Schramm et al., 1989, Thomas et al., 1995) and meteors (Trigo-Rodríguez (2003) (filled squares), as well as five meteors from the Perseid shower (Trigo-Rodríguez et al., 2003) (dots). The arrows show two possible paths of evolution in primitive protoplanets.

of some aggregate IDPs. A disproportional large fraction of the anhydrous IDPs in that study contained diopside (Zolensky and Barrett, 1994). Diopside is among the *ISO* astrominerals and was found to be heavily damaged by interactions with energetic particles in an anhydrous porous aggregate IDP (Figure 1d). Sub-chondritic Ca/Si ratios may well be common for Perseid meteors with a $>CI$ SiO_2 content (Borovička, 2005).

When the low-Ca cluster (Figure 7, dots) represents the main property of Perseids, it raises the possibility that hydration had efficiently leached Ca from anhydrous dust with an initially chondritic Ca content. If so comet Swift-Tuttle should have pockets or veins of Ca-sulfate and Ca-carbonate (salt) minerals such as in hydrated chondritic IDPs, CI1 and CI2 meteorites. Alternatively, the low-Ca cluster indicates an indigenous low-Ca content of these anhydrous Perseid meteoroids and the high-Ca meteoroid simply had chondritic composition and was ejected from a different part of the nucleus. Or, the high-Ca composition was due to co-accreted interstellar carbonate grains, *viz.* calcite ($CaCO_3$) that was detected in dust shells around evolved

stars (Kemper et al., 2002). Meteor showers offer excellent opportunities to ‘map’ the physical, chemical and mineralogical variability within primitive rubble-piles bodies but much more data will be necessary on individual meteors, including knowledge of the hydrogen (OH; H₂O) content of meteoroids.

5.3. TROILITE AND PERSISTENT METEOR TRAINS

The persistent train of the Yukon fireball had an initially red orange color and caused a foul odor. Murad (2001) suggested that heterogeneous processes based on Fe-sulfide (troilite; FeS) chemistry could explain the observations. A subset of the proposed reactions produced SO₂ suggesting that sulfur was produced during flash heating. A mineralogical study of flash heated sulfide IDPs during deceleration in the Earth’s atmosphere found inclusions of elemental sulfur in pyrrhotite (Fe₇S₈) that, rather than FeS, is the dominant sulfide (Rietmeijer, 2004; Figure 4b). The study showed that sulfur vapor was released from sulfides. Sulfur might react with atmospheric oxygen, suggesting the proposed reactions (Murad, 2001) that produced SO₂ and SO are the most likely ones to explain the Yukon fireball phenomena, including the foul odor after sulfur oxides had reacted with telluric water to H₂S.

6. Conclusions

In this paper I try to understand one of the most spectacular phenomena in the sky using measured porosity, mineralogy and chemistry of interplanetary dust and meteorites. I offer examples how this information could be used to explain certain meteor observations. Ideally one would like to have surviving debris from each meteor but herein lays the core of the issue. What I have described is the next best thing that, if it can be made to work, would provide a tool to map diversity and similarities among debris from known primitive asteroidal and cometary sources.

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PREPARING FOR HYPERSEED MAC: AN OBSERVING CAMPAIGN TO MONITOR THE ENTRY OF THE GENESIS SAMPLE RETURN CAPSULE

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Abstract. The return of the Genesis Sample Return Capsule (SRC) from the Earth's L1 point on September 8, 2004, represents the first opportunity since the Apollo era to study the atmospheric entry of a meter-sized body at or above the Earth's escape speed. Until now, reentry heating models are based on only one successful reentry with an instrumented vehicle at higher than escape speed, the 22 May 1965 NASA "FIRE 2" experiment. In preparation of an instrumented airborne and ground-based observing campaign, we examined the expected bolide radiation for the reentry of the Genesis SRC. We find that the

expected emission spectrum consists mostly of blackbody emission from the SRC surface ($T \sim 2630$ K @ peak heating), slightly skewed in shape because of a range of surface temperatures. At high enough spectral resolution, shock emission from nitrogen and oxygen atoms, as well as the first positive and first negative bands of N_2^+ , will stand out above this continuum. Carbon atom lines and the 389-nm CN band emission may also be detected, as well as the mid-IR 4.6- μ m CO band. The ablation rate can be studied from the signature of trace sodium in the heat shield material, calibrated by the total amount of matter lost from the recovered shield. A pristine collection of the heat shield would also permit the sampling of products of ablation.

Keywords: Astrobiology, fireball, Genesis, meteor, reentry, sample return capsule, thermal protection system

1. Introduction

The *Meteoroids 2004* conference was held at the University of Western Ontario, London, three weeks before the scheduled return of the Sample Return Capsule (SRC) of NASA's Genesis mission on September 08. The return of the Genesis SRC was the first opportunity since the Apollo era to study bodies entering the Earth atmosphere at or above escape speeds. At the meeting, we reported on the process of bringing together an instrumented aircraft campaign (the *Hyperseed Multi-Instrument Aircraft Campaign*) to observe this artificial bolide. We called for further ground-based observations to expand the range of possible measurements.

As part of the preparations for this mission, preflight predictions were performed using the SRC entry trajectory and entry vehicle shape to generate the continuum fluid dynamic flowfield solutions and the expected radiation spectra. This information was used in selecting the instrumentation for remote sensing of the fireball. This report summarizes those predictions.

At the time of writing, the reentry has occurred. Other opportunities will follow (Table I) when the Stardust (Jan. 2006) and Hayabusa (June 2007) SRCs will enter Earth atmosphere (Desai et al., 2000). These fireball observations can help us better understand natural asteroid impacts and can help improve the design of thermal protection materials for future Crew Return Vehicles that will bring people back from the Moon and Mars.

2. Scientific Rationale

2.1. SAMPLE RETURN CAPSULE ENTRY AS AN ARTIFICIAL METEOR

Natural impacts of meter-sized asteroids are extremely rare and unannounced, but represent a significant amount of matter falling in on Earth. Their arrival in the atmosphere is heralded by a brilliant flash of light and a burst of sound waves. No observations have been targeted at the specific

TABLE I

Opportunities to study space vehicles entering the atmosphere above Earth escape Speed

	Genesis	Stardust	Hayabusa
Date:	Sept. 08, 2004	Jan 15, 2006	June 2007
Time (local):	9:52:47 a.m. MDT	3:00 a.m. MDT	Night time
Elevation Sun:	27°	Night time	Night time
Moon phase, elevation:	0.7, 72°	1.0 (full), 68°	t.b.d.
Mass (kg):	225	45.8	18
Diameter:	1.52 m	0.811 m	0.40 m
Entry speed (@125 km):	11.0 km/s	12.9 km/s	12.2 km/s
Entry angle:	8.0°	8.0°	12.0°
Attack angle:	2.5°	3.0°	
Spin rate (rpm):	5	15	2
Peak brightness:*	-6.4	-6.7	-5.2
Peak heat rate (W/cm ²):	700	1200	~1500
Peak deceleration,	28	34	45
(Earth g's):			
Landing site:	UTTR, Utah	UTTR, Utah	Australia
Heat-shield material:	carboncarbon	phenolic impregnated carbon	phenolic ablator
Thickness	1.5" over insulator	2"	
Sample returned:	solar wind	comet + I.S. dust	asteroid debris

* From 100 km, V – magnitude if blackbody emission only.

aspects of ablation and atmospheric chemistry that are important for evaluating the role of meter-sized bodies in the exogenous delivery of organic matter to Earth at the time of the origin of life, for example. Until now, nearly all available data has come from staring instruments that are used to “listen” for clandestine nuclear tests and rocket launches and to recover meteorites.

The exogenous delivery of organics by small bodies of the solar system was the topic of past *Leonid Multi-Instrument Aircraft Campaigns*, which targeted the “meteoroids” peak, cometary dust, and the rarefied flow conditions of meteoroids smaller than the mean-free path of air at the altitude of ablation (e.g., Jenniskens et al., 2000a, b). *Hyperseed MAC* will target the meter-sized asteroids, the source of meteorites and rare fireballs, bodies large enough to form a hypersonic shock wave. Meter-sized “boulders” form a second peak in the terrestrial mass influx curve. They could have been the dominant source of organics and water at the time of the origin of life. Water entrapped in primitive asteroids has the D/H ratio of our ocean. Alternative sources of organic matter are giant impacts by asteroids and comets of ~10 km in size and ~150 μm sized meteoroids, each delivering under different

circumstances. Giant impacts created high-pressure, high-temperature, shock waves that destroyed most of the organic matter. Meteoroids, on the other hand, were too small to form shocks, and their organic matter was ablated as a haze of large molecules.

Somewhere in between are the fireballs that result from the impact of meter-sized asteroids. They deposit 99.9% of their mass in the Earth's atmosphere in a complex process of ablation, spallation, fragmentation, and shock layer chemistry. The organic matter in the asteroids is deposited in the atmosphere in the form of atoms, small molecules, large molecules, soot, and dust. Carbon atoms and molecules will react chemically with the atmosphere in the shock layer and wake, which could result in organic compounds enriched in functional groups that are different from those found in meteorites.

The tiny fraction that survives in the form of meteorites can be studied in the laboratory. Although meteorites give information on the initial composition of the organic matter and its association with minerals and water, such studies do not address what happens to the bulk of the organic matter in the fireball phase. No samples in our dust collections are with certainty from asteroid entries, although some particles appear to be ablation droplets similar to those found partially attached to the fusion crust of meteorites. Many recovered micrometeorites appear to be of asteroidal origin, but their predominant CM composition suggests they derive from small meteoroids.

We do not know if carbon can survive the shock layer conditions in reduced form as molecules or solid particles. In the present day atmosphere, organic molecules and soot are quickly dispersed and blend with our natural and man-made environment. Laboratory experiments of meteorite ablation mimic, but do not reproduce exactly, the physical conditions in natural fireballs. In particular, it is impossible to reproduce at the same time both the heat flux to the surface from convective flow and from radiation generated just behind the shock.

We understand that the SRC reentries are not natural bolides, but they have similar flow conditions and they provide simpler and well known experimental starting conditions to study various aspects of the ablation process. Their size (0.8–1.5 m) is in the range of asteroid fragments and comet boulders (~4 m). The SRC entry speed (11.0–12.9 km/s) is high enough to have a significant contribution from radiative heat flux and sample the lower end of the range for natural asteroid entries (11 to about 30 km/s, peaking around 15 km/s). The Stardust SRC will have the highest heating rate for any Earth returning vehicle to date. The sample return capsules come in at a particular entry angle (~8°), creating a nice long duration grazing fireball, while asteroids cover the full range from 0 to 90°. The sample return capsules are blunt objects, setting up a relatively wide shock wave, the size and shape of which affect the heat flux. Asteroids, too, are blunt objects, unlike most sharp re-entering objects studied for military

applications. The SRCs are spun up to stabilize the reentry. Natural asteroids spin too, albeit with a spin vector relative to the forward direction of motion that can be different from that of the SRCs. Overall, the conditions in the shock wave are, as far as the processing of the ambient air and heat flow to the surface are concerned, representative of natural bolides. Finally, a big advantage of SRC reentries over natural fireballs is that their emission spectrum is not dominated by metal atom line emissions from the ablated matter. This makes it possible to study the much weaker shock emissions.

An important difference between SRCs and asteroids is that the rate of ablation is low. This will affect the abundance of trace compounds in the ablated layer over the surface. The expected ablation products along the stagnation streamline at peak heating are dominated by CO, C and C₃ (Olynick et al., 1999). Triatomic carbon, C₃, and CO mole fractions drop rapidly as the temperature rises in the boundary layer. A similar analysis for Genesis is not published, but we expect the CO mole fractions to be roughly the same but the C₃ and H values to be much lower, depending strongly on the peak surface temperature. Most of the ablation would be due to oxidation, leading to CO and carbon atoms (from the decomposition of CO into C+O away from the surface). Natural asteroids can have lower and higher heat fluxes, depending on entry conditions. They, too, may combust their organic matter incompletely. Such chemistry is of interest to astrobiology. Most of the Genesis carbon-carbon heat shield is ablated over a period of about 40 s around peak heating, when the SRC is between 80 and 50 km altitude (bolides ablate between 80 and 20 km).

The asteroids are also prone to catastrophic fragmentation, which leads to much mass being lost in small debris fragments. The sample return capsules are certainly not intended or expected to catastrophically fragment.

2.2. A TEST OF A THERMAL PROTECTION SYSTEM

The Genesis SRC heat shield material is flown for the first time under these high entry-speed conditions. The actual conditions of descent have never been simulated in the laboratory for all relevant parameters at the same time. The NASA/Ames Arcjet Facility mimics the convective heat flow well (albeit with pre-dissociated air), while shock-tube experiments provide good measurements of the radiative heat flux (albeit for a brief moment of time). Radiative heat flux becomes important relative to convective heatflux for speeds in excess of $V > 11$ km/s. This is clearly shown in the models for heat flux of two Apollo missions (Figure 1). In the case of Genesis, about 5% of the heat flux is expected to be due to radiative heat flux.

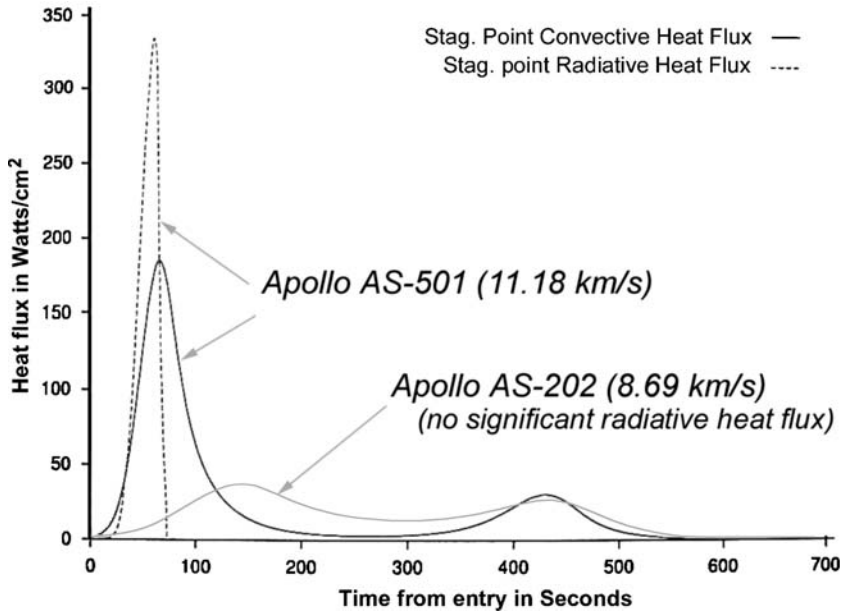


Figure 1. Convective (solid line) and Radiative (dashed line) heat flux as a function of time from entry (in seconds) for Apollo returns from Earth orbit (AS-202) and from the Moon (AS-501).

Only one successful reentry with a blunt instrumented vehicle at higher than escape speed has been studied in the past. The 22 May 1965 NASA “FIRE 2” experiment consisted of an instrumented subscale model of the Apollo crew return vehicle, boosted to 11.36 km/s. Telemetric data on heat flux were sent to the ground and that data is used even today. No remote observations were made. The Stardust and Genesis thermal protection calculations are based on these FIRE 2 data. The earlier 14 April 1964 NASA “FIRE 1” experiment, boosted to 11.25 km/s, failed because the booster caught up with the model after separation. The lack of data prompted the Japanese space agency JAXA to launch “DASH” – *Demonstrator of Atmospheric Reentry System with Hyper Velocity* on 4 February 2002, boosting to 10.0 km/s a flight model of the Hayabusa SRC (formerly MUSES-C). The experiment failed because SRC and booster did not separate (Maemura, 2002).

The FIRE 2 data, and results from Apollo 4, are still being used to calibrate the current NEQAIR models that predict the amount of radiative heating expected. NEQAIR is based on first principles, line-by-line methodology. Emission models are based on spectroscopy data. While that theory is well understood, it is the excitation and transport conditions that are difficult to model and are presently calibrated by few actual entries

over a limited range of ablation and entry conditions. Additional flight data over a wide range of entry conditions are needed to provide validation data.

In addition to questions of radiative heating, there are specific issues with the design and materials used in the thermal protection system. If a meteoroid impacted the heat shield prior to entry, the brittle material may have been damaged, as was the carbon-carbon wing edge of the Space Shuttle Columbia (STS-107) during launch. In addition, light can penetrate the SRC carbon fibre structure, heating lower layers, and possibly resulting in spallation. If spallation turns out to be more important than expected, more of the heat shield will be lost.

The surface of the Genesis SRC is a 1.5 inch thermally-conductive high-density (1.8 g/cm^3) high-temperature (2870 K) deposited carbon-carbon sheet (made of fibers of highly ordered pyrolytic carbon) on top of a low density carbon foam insulator. Thus, carbon debris may be created in a manner not typically expected for asteroids. The known properties of the starting material, however, permit testing of the ablation rate as a function of surface temperature against models. Laboratory experiments involving both carbon-carbon and natural meteorite materials can then provide a context to understand the differences in their ablation properties.

The lid of the capsule will pop off at about 36 km altitude, 2.2 min after entering Earth's atmosphere, when a drogue chute is expected to deploy, followed by a parafoil chute almost 4 min later at 6.1 km altitude. The parachute will be grabbed with a hook carried by a helicopter before hitting the ground at the Utah Test and Training Range (UTTR) to prevent the sample panels from breaking. This pristine recovery of the heat shield makes it possible to sample carbon flakes and recondensed soot deposits that are products of the ablation.

3. Predicted Emissions

The Genesis SRC might first be seen at ~100 km altitude (Figure 2), where the surface temperature starts to rise significantly (Figure 3). Peak surface temperature, and peak absolute brightness, is at about 60 km altitude and +59 s after passing the 135 km altitude point. Highest deceleration occurs at ~50 km altitude, about 66 s in flight. Once the forward motion has been stopped, the object will fall at a steep angle onto U.T.T.R. The point of impact is uncertain to many tens of kilometers (Desai and Cheatwood, 1999), but the trajectory is expected to be better known after the Sample Return Capsule has been released from the spacecraft prior to reentry.

Stardust will have a similar approach trajectory coming from the WNW and landing at U.T.T.R. The higher entry speed is somewhat compensated by

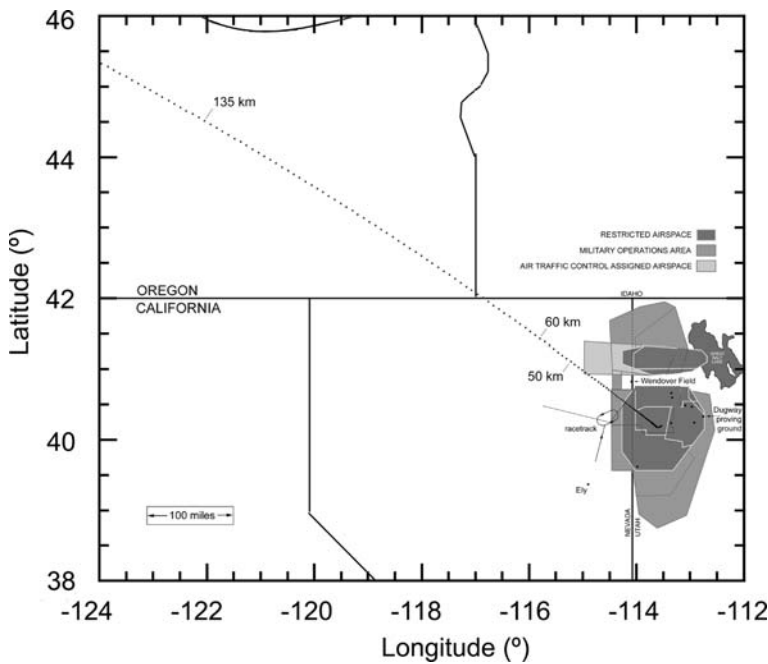


Figure 2. Flight trajectory (intervals in 1 s flight time), with position of the FISTA aircraft (“racetrack”) and location of Utah Test and Training Range.

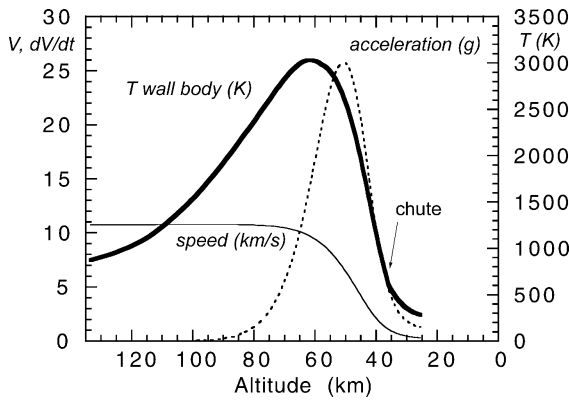


Figure 3. Genesis SRC entry conditions of speed, deceleration, and peak surface temperature versus altitude.

its smaller mass, but the peak heating temperature will still be higher. Stardust arrives faster than Genesis and has a Phenolic Impregnated CARbon ablator heatshield (PICA, Tran et al., 1996). Because of that, the peak surface temperature will not rise above 3500 K, at which temperature a convective surface layer of compounds (CO, C₃, air) carries away heat and in

effect blocks boundary layer energy from reaching the surface. A similar effect will occur in natural bolides (at lower temperatures), from ablated organic and mineral components. The SRC reentry experiment will provide information on the efficiency of carbon in protecting and cooling the surface in this manner, by simply measuring the surface temperature as a function of altitude and taking into account the measured radiative heat flow derived from the intensity of air plasma emissions (convective heat flow assumed known).

3.1. BLACKBODY RADIATION

If the surface temperature of the SRC rises above about 2500 K, we expect that the blackbody radiation from the surface will dominate the total light output at visible and near-IR wavelengths (Figure 3). The blackbody radiance is a strong function of surface temperature $\sim T^4$.

The distribution of surface temperatures has a small but significant impact on the expected wavelength dependent signal. Surface temperatures will range from about 2400 to 2923 K, causing light emission to peak near 1 μm . Figure 4 shows the blackbody curve for different temperatures and an

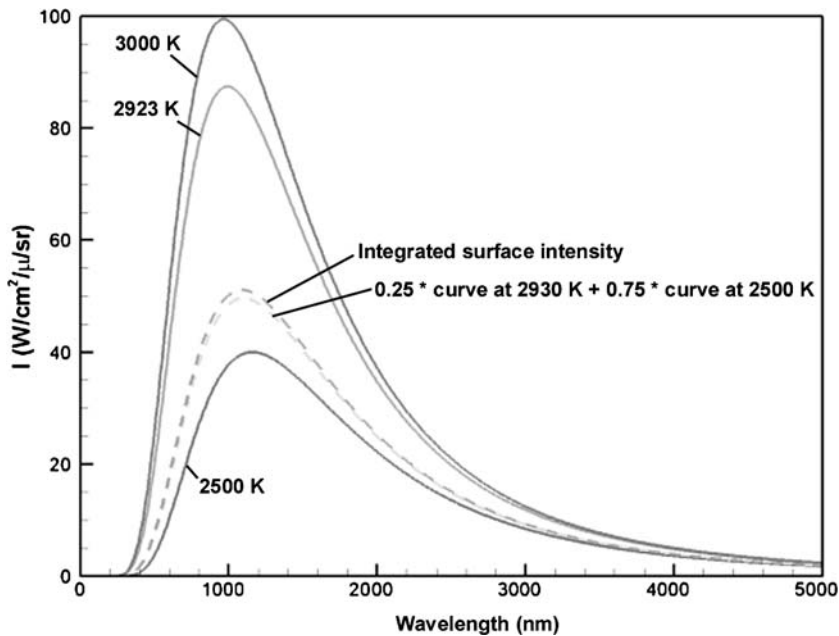


Figure 4. The wavelength dependent SRC surface blackbody emission for representative temperatures.

“Integrated Surface Intensity” calculated by adding the area-weighted contributions of each surface point.

The maximum surface temperature occurs at the stagnation point (Figure 5), with possible hot spots at the forebody penetration points. These hottest surfaces represent only a small fraction of the total and do not change the shape of the continuum spectrum much. Nevertheless, a small skew may be observed in the blackbody curve, if it can be measured precisely enough over a wide wavelength range.

The observed emission will be characterized by the intermediate temperatures off the stagnation point, with a mean at around 2610–2634 K. The integrated distribution would suggest a temperature of $T \sim 2634$ K at short wavelengths near 700 nm, but $T \sim 2610$ K at longer wavelengths near 1600 nm (Figure 6). These differences may be sufficient to retrieve information about the surface temperature distribution from remote sensing observations. Predicted surface distributions can be compared to the measured intensity distributions to determine the range of possible peak temperatures and distributions.

The blackbody emission alone would make the object bright enough to be detected in broad daylight at visual wavelengths, albeit with some difficulty. Figure 7 shows the expected SRC brightness based on the blackbody

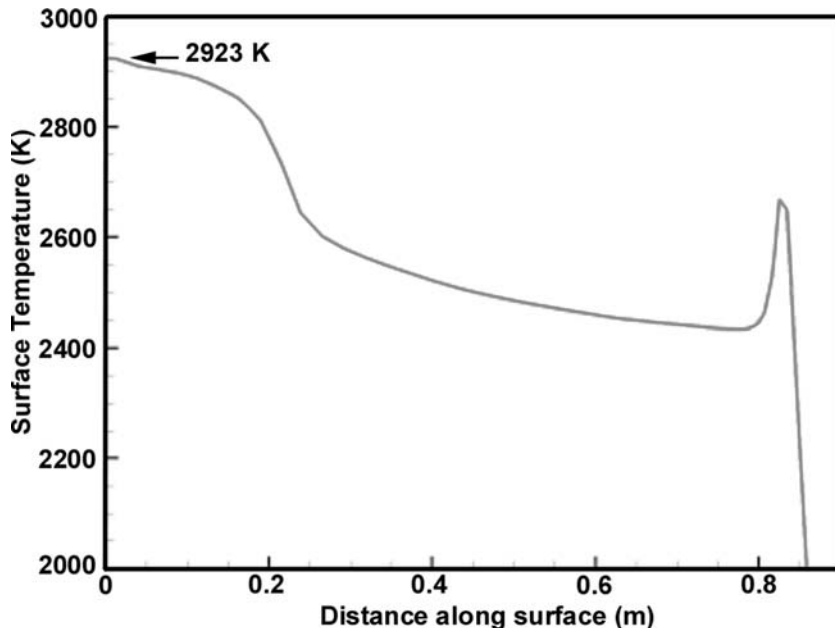


Figure 5. Plot of the radial distribution of the Genesis SRC surface temperatures. A peak temperature of 2923 K is found at time = 126 s for the REF-08 Trajectory. A fully catalytic, radiative equilibrium wall is assumed.

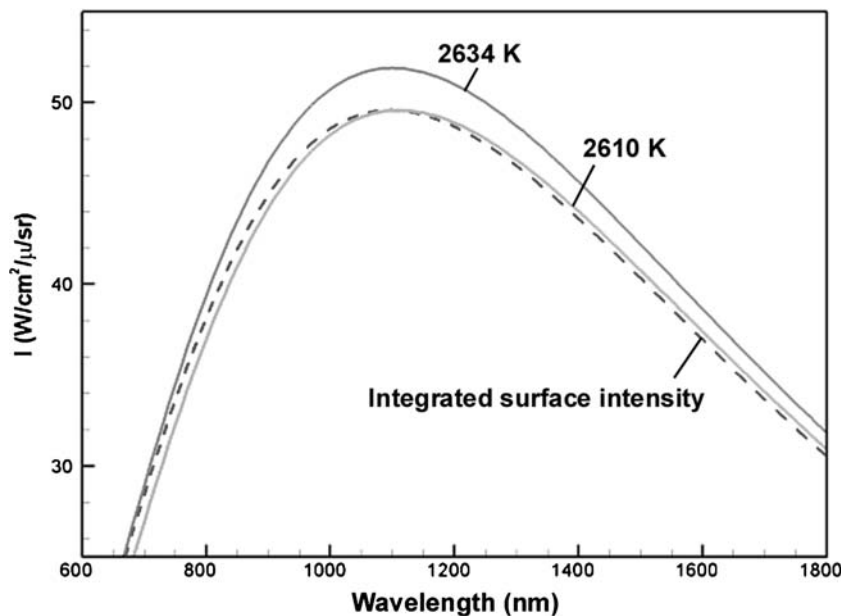


Figure 6. Sum of blackbody emissions (dashed line) from the model shown in Figure 5, with blackbody curves at $T=2610$ and $T=2634$ K (solid lines) superposed to see the anomalies.

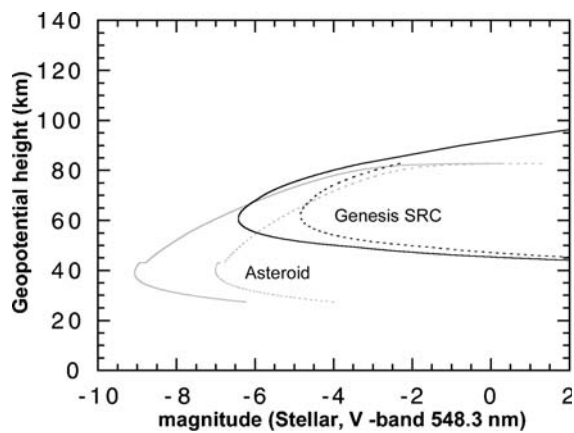


Figure 7. Stellar V magnitude of the SRC in terms of anticipated absolute (=at 100 km distance, solid line) and apparent (from the perspective of FISTA, dashed line) brightness. The result for blackbody emission only (frontal face, black line) is compared to the entry modeling of a natural bolide (gray line), assuming a mass of 225 kg at 11 km/s at an entry angle = 8° .

emission alone. The SRC entry was also studied with the more comprehensive asteroid entry bolide model of Doug Revelle (LANL). This model assumes that the light is proportional to the time rate of change of the kinetic

energy (through the differential panchromatic luminous efficiency). The result is shown in Figure 7. The bolide's heating rate is found to peak at about 55 km at a rate very near to the literature estimate for the Genesis SRC: 1000 W/cm^2 . Nevertheless, its time rate of change is predicted to peak closer to 38 km. This is where the light peaks in the bolide model. The small increase in brightness marks the onset of turbulence in the shock, something that may be observed.

3.2. SHOCK RADIATION

Radiation produced in the high temperature region immediately behind the shock is the cause of radiative heat flux. This radiation is emitted from excited (higher energy) electronic states of atoms/molecules and atomic/molecular interactions with free electrons. Figure 8 shows the physical conditions and chemical abundances in the shock along the stagnation line. Emission processes are generally well-understood, based on laboratory spectroscopic data and calculations. The rate of produced emission is less certain, because it depends on the excitation conditions and gas density in the shocked layer, as well as the presence of ablation products. Traditional computational fluid dynamics (CFD) codes compute the number of atoms/molecules in the ground electronic state. An excitation model is needed to calculate the number of electronically excited molecules and the distribution of those molecules among vibrational and rotational states based on CFD results. Models that describe the amount of absorption in the shocked layer are needed to compute the transport of photons from the shock region to the surface and the radiative heating at the surface. The theory for such models is well understood, but the necessary absorption coefficient data is lacking.

One of us (J.O.) performed CFD (DPLR) calculations for 11 species (N_2 , O_2 , NO , N , O , N_2^+ , O_2^+ , NO^+ , N^+ , O^+ , e^-) at 7 points on the preliminary Genesis trajectory called "REF-08", which is close to the actual trajectory. Based on the CFD result at each point, NEQAIR calculations were performed over the wavelength range $0.3 < \lambda < 1.0 \text{ } \mu\text{m}$. Shorter wavelength measurements are not possible due to atmospheric absorption. Longer wavelength lines and bands are currently not included and/or verified in the NEQAIR model. N and O atomic lines, bound-free & free-free continuum, and N_2 , O_2 , and NO molecular bands are included. The shock layer emission in the direction of the observing plane is assumed to be optically thin. We also assume there is no atmospheric absorption between the capsule and the observing plane, which is reasonable. At times prior to $t = 40 \text{ s}$, the SRC may not be in the continuum flow regime and the Navier-Stokes results are suspect.

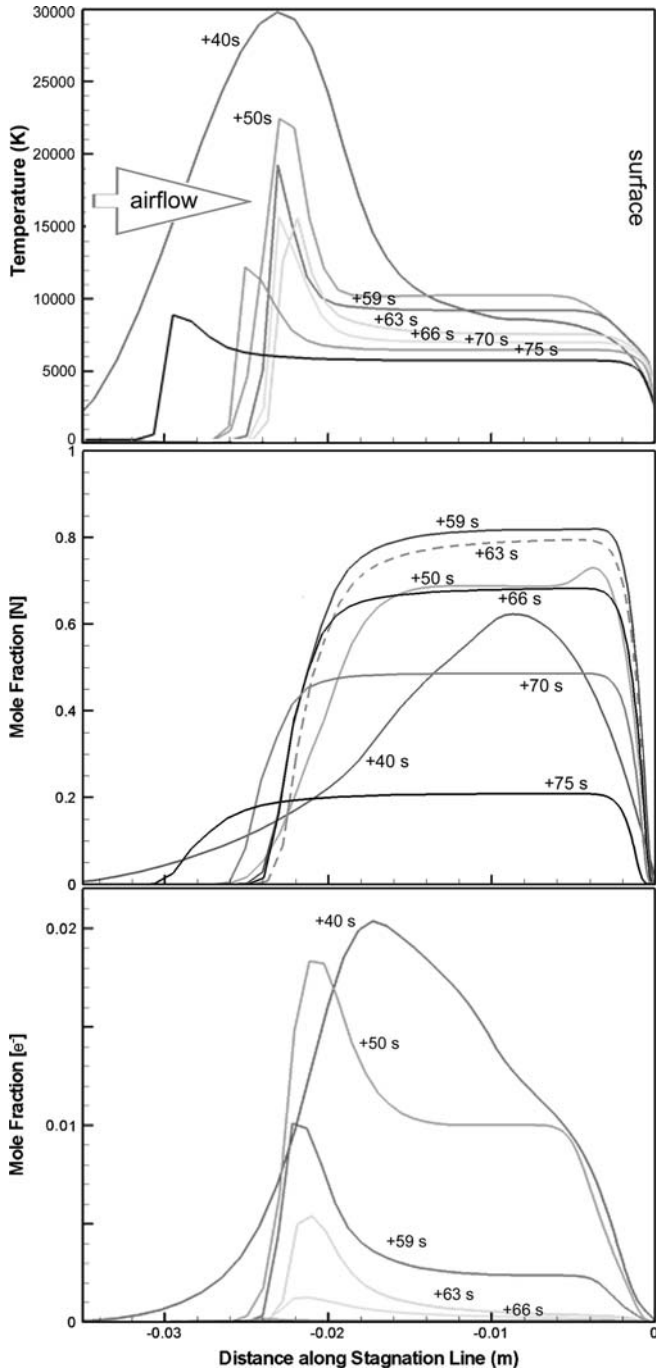


Figure 8. Shock conditions at different times during descent. On the X-axis is the distance along the stagnation line (m), on the vertical axis the mole fraction of neutrals and of electrons in the shock layer. The air is impinging from the left, while the surface of the SRC is on the right of the diagrams.

Figure 9 shows the sum of shock emissions and surface blackbody radiation during peak heating. The excitation temperatures in the shock vary, but the primary radiators include the $\text{N}_2[1^+]$ band, the $\text{N}_2^+[1^-]$ band, and N and O lines. There is also a weak continuum from the air plasma. The shock radiation is primarily emitted from the “overshoot” region immediately behind the shock wave and is stronger in the early phases of heating. The adopted radiative equilibrium stagnation point temperature ($T=2410\text{ K}$) is an upper bound on the temperature. The blackbody curves represent the integrated average surface temperatures expected at different times during descent. The shock layer emission shown represents a volume-averaged value.

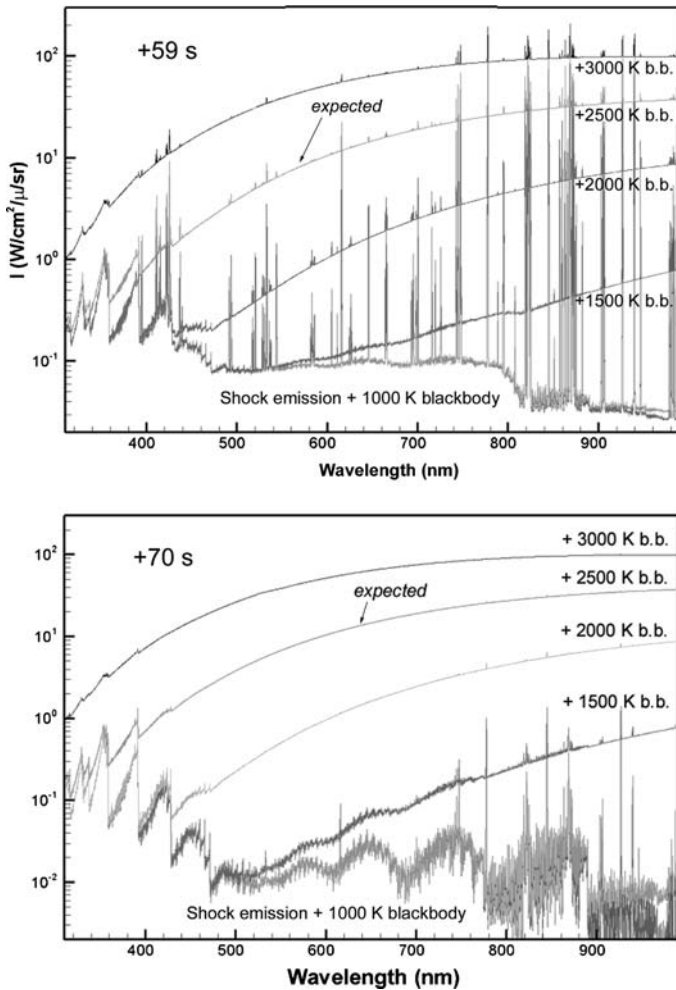


Figure 9. Expected optical emissions from shock radiation (stagnation temperature 2410 K, radiative equilibrium) at $t = +59\text{ s}$ (peak heating) and $t = +70\text{ s}$ after entry, superimposed on various blackbody radiation levels.

We find that band emission below 400 nm and the near-IR atomic lines of oxygen and nitrogen should be discernible even early in the trajectory. At a spectral resolution of 1 nm, band emission below 450 nm and atomic lines should be discernible at peak heating. Band emission below 400 nm and atomic lines should be discernible past peak pressure, when both shock emissions and surface emissions are weaker. A higher spectral resolution will cause the atomic lines to stand out better from the blackbody background.

The line ratios among nitrogen and oxygen lines (Figure 10) are useful thermometers of excitation temperatures (for a given species) and chemical abundances in the air plasma (ratio of N/N^+ versus O/O^+). The absolute line intensities provide deviations from Local Thermodynamic Equilibrium. The optical and near-IR emissions are proportional to the far UV emissions at ~ 120 nm that can not be seen from the ground or air, but which are important for radiative heating. The air plasma emissions need to be resolved from the blackbody background continuum at sufficient signal to noise to measure line intensity ratios precisely enough.

3.3. EMISSIONS FROM ABLATION PRODUCTS

We did not yet consider the effect of surface blowing and ablation products (CN, CO, C, C_2 , etc.). Preliminary calculations of ablation products show that the CN violet band around 400 nm may be detectable, even though abundances are expected to be low (Olynick et al., 1999). CN is generated from the interaction of carbon atoms from the surface with the nitrogen in the shock layer. The emission may be more intense for the Stardust reentry, which is expected to ablate significant amounts of carbon in the form of atoms and C_3 . At mid-IR wavelengths, the $4.7\text{-}\mu\text{m}$ CO band should be

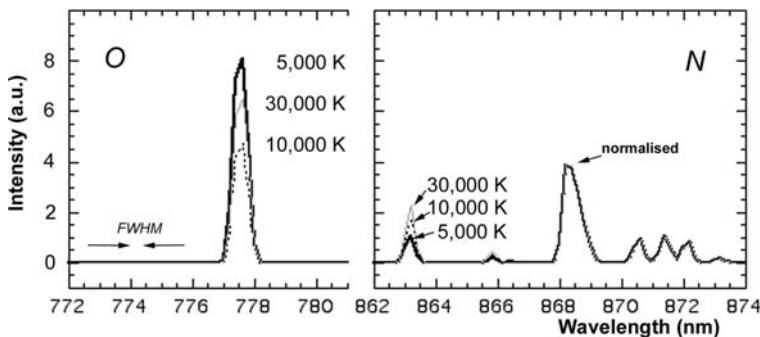


Figure 10. The various nitrogen and oxygen lines at 0.34 nm resolution for different excitation temperatures (in K).

detectable if detected on top of a well defined blackbody slope. The emission is expected to be broad. The Stardust heat shield will also generate significant amounts of C, and C₃. C₃ has a broad emission band just above the mid-IR CO band.

In the process of making the carbon–carbon material, a binding component containing sodium left traces in the fibers. We propose to measure ablation rate from the sodium D-line intensity, even when the rate is low. Sodium is an atom with a zero energy ground state and high transition probability, but is also expected to rapidly ionize in the shock layer after leaving the surface. Hence, the intensity of the sodium emissions are expected to be proportional to the rate of ablation. Because of that, the sodium emission can serve as a tracer of the ablation profile. The ablation rate can be calibrated from the total amount of material lost from the recovered heat shield. Atmospheric trace sodium found between 90 and 80 km does not contribute significantly to the spectrum, as is demonstrated by sodium-deficient meteor spectra.

The forebody penetrations, too, may cause strong metal atom line emissions, but from the metals that underlay the carbon–carbon heat shield, which include aluminum and titanium. We also recognize a small probability of heat shield spallation, which can lead to small fragments being lost. Those could be seen as points of light quickly trailing the capsule due to higher surface-to-mass ratio and rapid deceleration.

A much more difficult target is the carbon atom line emission. The strongest accessible lines of atomic carbon in ground or airborne observations are in the near-IR at 966, 991, and 1069 nm. Thirty-four seconds in flight, the flux of ablated material is 13% of the amount of impinging air, the highest ratio. The ablated materials penetrate deeper into the shock layer early on in the trajectory. From that, the expected emission spectrum (Figure 11) has carbon lines nearly as strong as nitrogen and oxygen lines in the 900–1100 nm wavelength region. To avoid blending and to bring out the lines from the strong continuum, a high spectral resolution < 1 nm is needed. Shown are data at 0.25 nm resolution.

Mid-IR measurements of CO (4.67 μm), and C₃ (5.2 μm) emission in the case of Stardust, would not only provide a measure of abundance of ablated compounds, but also the temperature of the emitting molecules from the band shape (expected to be anywhere from $\sim 3,500$ – $10,000$ K). The ratio of CO and C₃ band strengths is a sensitive indicator of the relative importance of oxidation and sublimation under the given conditions. The observations would need to be capable of measuring the band strengths above the (relatively weak, peak at shorter wavelength) continuum, taking into account a possible variable water vapor absorption band above 5.3 μm . Above 1,000 K, the 4.67 μm CO band has a distinct band head at 4.3 μm , a peak at 4.5 μm , and the band stretching to longer wavelengths out to 5.5 μm (Russell et al., 2000). Although the band head falls in the telluric CO₂ absorption, the

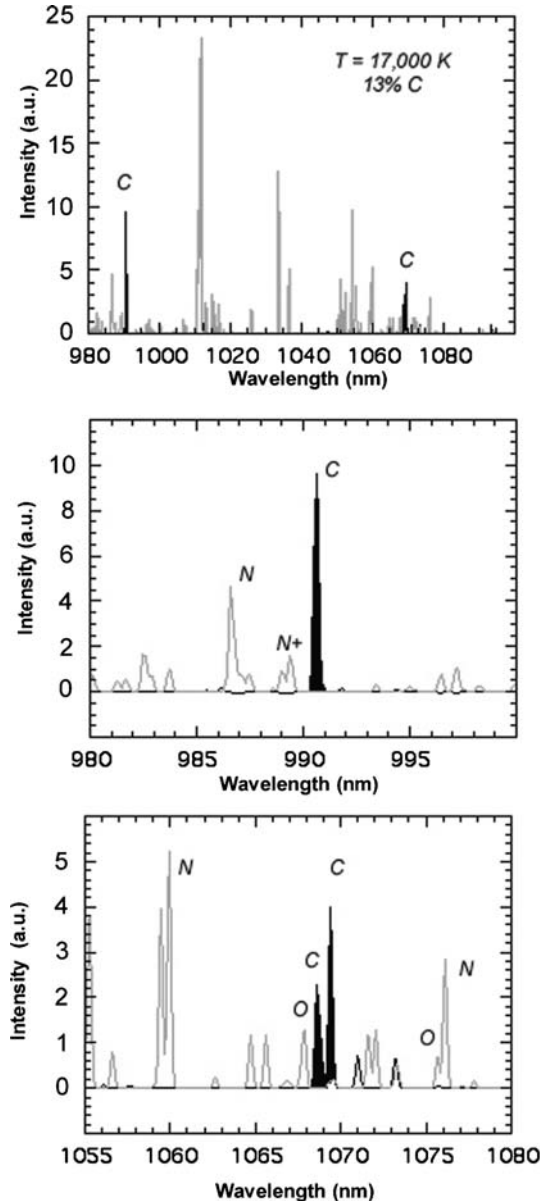


Figure 11. The possible intensity of carbon atom lines in relation to N and O lines for an excitation temperature of $T = 17,000$ K.

attenuated emission can be recognised because the CO band falls off steeply, by a factor of 40, from 4.67 to $4.0 \mu\text{m}$. Hence, it is important to measure the continuum in the $3.5\text{--}4.0 \mu\text{m}$ region to measure the CO band strength reliably. With a peak ablation rate of 0.5 kg/s for Genesis (and 0.2 kg/s for

Stardust), nearly all of which goes into CO and, using that optically thin CO at 3500 K emits at a rate of 3 photons/sr/micron/molecule at the instrument resolution (Russell et al., 2000), the CO band intensity would be 145% of the continuum emission at the peak of ablation.

The expected emissions of hot complex carbon molecules, clusters, flakes, and soot grains $< 10 \mu\text{m}$ in size have peaks at 6.2 and $7.7 \mu\text{m}$ due to C–C stretch and bend vibrations. Reactions with atmospheric water and hydrogen can result in a C–H emission band at $3.4 \mu\text{m}$, as will the Stardust phenolic impregnated carbon. Little is known about the expected amounts of these materials, which can be deduced from excess emission in the 6–8 μm range.

3.4. OTHER INTERESTING PHENOMENA

Any wake emissions are thought to be dominated by NO₂ chemiluminescence in the visible. This is a broadband emission hard to distinguish from continuum.

The strong hypersonic shock wave is expected to generate an infrasound signal on the ground. The predicted peak-to-peak amplitude pressure difference is 1–5 Pa, derived from Apollo entry data from various NASA reports, scaled to the much smaller size of the Genesis SRC.

Worth investigating is also the possible existence of a large photoionization halo generated by “precursor” UV radiation from the shock wave. Radio echoes have been detected before from a manned space vehicle returning to Earth (Lin, 1962) and attributed to this effect. The UV-precursor mechanism had been invoked earlier to explain meteor head echoes (Cook and Hawkins, 1960). The effect has been demonstrated, for near continuum flows, in laboratory shock tube experiments (Presley and Omura, 1970). The ionizing radiation is believed to be from electronic states in N₂ sufficiently energetic to ionize O₂ (Marrone and Wurster, 1970).

4. Hyperseed MAC

Motivated by this rare scientific opportunity, we have worked to provide an airborne platform for a diverse team of researchers. The USAF/412th TW operated “FISTA” aircraft, an NKC-135, and the same aircraft used in past Leonid MAC missions (Jenniskens et al., 2000b), has 20 upward looking windows of 12” inch diameter optical quality glass. USAF Hanscom AFB will provide the optical windows, including one of Germanium for mid-IR observations. The aircraft permits viewing of the SRC above weather, water vapor, smoke of wild fire and other aerosols, providing a low sky background

in the visual and near-UV, and low scintillation for imaging. The SETI Institute will provide the logistic support.

Participants (Figure 12) will be from NASA Ames Research Center, the SETI Institute, the Aerospace Corporation, the University of Alaska, the USAF Academy, Utah State University, the University of New Mexico, Los Alamos National Laboratory, Sandia National Laboratory, Lockheed Martin, and U.C. San Francisco. An overview of instrumental capabilities is given in Figure 13. Spectroscopic instruments will be mostly slit-less, but



Figure 12. Hyperseed MAC Genesis team at Edwards AFB, California (Sept. 03, 2004). Photo: USAF/412th TW.

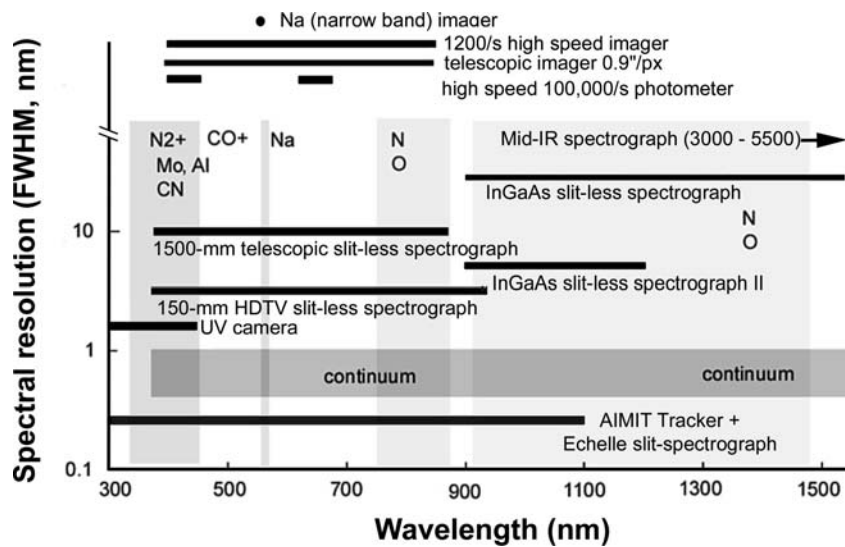


Figure 13. Outline of instrumental capabilities.

we will also include a tracking device (“AIMIT”) with a high-resolution slit-spectrograph to resolve atomic line emissions. Some redundancy will be provided. Optical and near-UV spectrometers will focus on the CN and N_2^+ emission bands, and the sodium and N & O atomic lines in the red and near-IR. Near-IR (InGaAs) spectrometers will measure the peak of the blackbody curve and any broadband molecular emissions in the range 900–1600 nm. Mid-IR sensors will study the blackbody emission tail and any CO and CO₂ vibration band emissions. High frame-rate imagers and photometers will observe any irregularities in light output, spallation, and the development of a UV halo. Telescopic systems are also included to attempt to obtain spatial features of SRC, but we do not expect to resolve features above ~10 m. These instruments will be hand-pointed, using pointing cameras with ~5–10° field of view, small enough to bring out the SRC from the bright daytime background. The nighttime reentry of Stardust will not require such restrictions.

Different instruments will cover different dynamical ranges in brightness and different spectral resolutions. Photometry will tie the various spectral ranges together (allowing for different beam filling factors and some redundancy).

This will be a one-day mission out of Edwards AFB in southern California to Oregon (~2 hour flight), where the aircraft will be positioned along the track of the approaching reentry vehicle so that the object has the lowest angular velocity upon approach (Figure 2). This permits observing the shock from the front, but also have a gradual increasing apparent motion on the sky to be able to study any wake. Because the measurements will be done from one location, the results from different instruments can be compared.

The airborne observations will be complimented, however, with a number of ground-based observations. In particular, an infrasound array will be installed at Wendover Airfield, Nevada (Figure 2). The array is composed of four, low-frequency pressure sensors with spatial wind-noise filters with a horizontal separation of ~50–100 m between individual sensors. The basic pressure sensor is a Chaparral microphone with flat response (3 dB band-pass) from 0.02 to 10 Hz for signal amplitudes as small as 0.01 Pa.

5. Conclusions

Preflight predictions performed using SRC entry trajectory, entry vehicle shape to generate CFD flowfield solutions, and theoretical radiation spectra show that blackbody radiation is expected to dominate the emissions, but there will also be significant shock emissions and emissions from ablated

compounds. An instrument suite was selected which is expected to provide appropriate sensitivity to wavelength and intensity of important features.

The mission will aim to confirm the average surface temperature and temperature profile due to the combined radiative and convective heat flux. We will attempt to measure the intensity of the shock emissions to estimate the contribution from radiative heat flux and perhaps detect the transition to turbulent flow. Detection of shock emission will also permit the study of the physical conditions for shock chemistry in natural bolides.

The ablation profile appears to be most readily studied from the expected sodium emissions, assuming that the sodium intensity is proportional to the number of atoms released per second into the shock. The possible detection of CO in the mid-IR can confirm that burning towards CO is the dominant ablation process. Imaging of any wake and sparks can confirm whether or not spallation occurred during descent.

These observations may assist in an accident investigation in the (remote) case of catastrophic failure during descent. Of particular interest in this regard is damage in space and the impact of the forebody penetrations on the ablation behavior of the heat shield.

Final note. At the time of writing, the Genesis SRC entry is behind us. The heat shield performed much as expected, but due to a technical design error, the drogue chute did not open. The Hyperseed MAC mission was executed much as planned. The observed entry trajectory was very close to that predicted hours before the reentry. Unfortunately, all narrow-field pointed instruments failed to acquire the SRC because an outdated trajectory file was used by mistake to calculate the pointing directions. Direct access to the latest predicted trajectories from the primary mission navigator source can help prevent this mistake in future missions. We did successfully acquire the SRC with staring broadband imagers from the plane and ground, providing surface temperature measurements, and also measured the sonic boom with the infrasound array. These data are still being reduced and the preliminary results were submitted to the accident investigation board.

Acknowledgements

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Editorial handling

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PHYSICAL PROPERTIES OF METEORITES AND INTERPLANETARY DUST PARTICLES: CLUES TO THE PROPERTIES OF THE METEORS AND THEIR PARENT BODIES

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Abstract. Meteorites, generally 1 cm or larger in size that are believed to sample asteroids, and interplanetary dust particles (IDPs), generally 5–50 μm in size that are believed to sample both asteroids and comets, span the size range of the meteors. Thus, the physical properties of the meteorites and the IDPs are likely to constrain the properties of the meteors and their parent bodies. Measurements of the density, porosity, longitudinal and transverse speeds of sound, elastic modulus, and bulk modulus, as well as imaging of the internal structure by Computed Microtomography indicate that unweathered samples of chondritic meteorites are more porous and have lower sound velocities than compact terrestrial rocks. In general, the IDPs are even more porous than the chondritic meteorites. The impact energy per unit target mass required to produce a barely catastrophic disruption (Q^*_D) for anhydrous ordinary chondrite meteorites is twice that for terrestrial basalt or glass, indicating that collisional disruption of anhydrous meteorites requires more energy than for a compact basalt. These results indicate that most stone meteors are likely to be weak, porous objects, and that the parent bodies of the anhydrous stone meteorites are likely to be more difficult to disrupt than compact terrestrial basalt.

Keywords: Cratering, density, interplanetary dust particles, impact disruption, meteorites, meteors, porosity

1. Introduction

Meteors are extraterrestrial particles, typically ranging from a few hundred micrometers up to centimeters in size, that vaporize during passage through the Earth's atmosphere, producing an ion trail. Trajectory analysis indicates that some meteors have orbital paths consistent with known comets while other meteors have orbital paths indicating an asteroidal origin. Some of the physical properties of the meteors can be inferred from their interaction with the Earth's atmosphere. For example, the density can be inferred from the deceleration. However, much of the information on the physical properties of meteors and their parent bodies is lost because most meteors are destroyed during atmospheric deceleration.

Samples of several types of extraterrestrial materials survive atmospheric deceleration and are available for laboratory study. Meteorites, ranging from ~1 cm up to meters in size, survive atmospheric entry because they have sufficient mass that they do not completely vaporize before hitting the ground. In a few cases, meteorites have been recovered from objects that produced visual meteor trails, allowing a direct comparison of the properties inferred from measurements during the meteor phase with measurements of the physical properties made on the recovered samples. The meteorites are believed to be samples of the asteroids, the Moon, and Mars. Meteorites come in a variety of types: stones, irons, and stony-irons. The stone meteorites are divided into two types: the chondrites, which are among the most primitive rocks of the early Solar System, and the achondrites, which experienced chemical differentiation after incorporation into their parent bodies. The chemical and mineralogical properties of the meteorites are described in a general way by Norton (2002) while the chondritic meteorites are described in detail by Brearley and Jones (1998) and the achondritic meteorites are described in detail by Mittlefehldt et al. (1998).

Interplanetary dust particles (IDPs), ranging from ~5 to ~50 micrometers in size, are collected from the Earth's stratosphere by NASA aircraft, using an impact collection technique (Brownlee, 1985). Polar micrometeorites, ranging from ~25 to several hundred micrometers in size, have been collected from the ices in Greenland, Canada, and the Antarctic (see e.g., Maurette et al., 1991). These small particles survive atmospheric entry because they have a large ratio of surface area to volume, thus they efficiently radiate away the heat generated by atmospheric deceleration, and never reach the high temperature required to produce a meteor trail. Many of the IDPs show minimal evidence for entry heating and alteration (as discussed in Flynn, 1989), thus they are believed to preserve the original properties of their parent body. Most of the polar micrometeorites melt on atmospheric entry. Some micrometeorites retain unmelted relic grains, which provide clues to their precursors (Beckerling and Bischoff, 1995), but the melted spheres have lost much of the information on the structure, density, and other properties of their parent bodies. Both the IDPs and the polar micrometeorites are generally believed to be samples of asteroids and comets. The chemical and mineralogical properties of the IDPs are described in detail by Rietmeijer (1998).

The IDPs and the meteorites span the size range of the meteors, with the IDPs being smaller than the meteors while the meteorites are larger than the meteors. Thus, the physical properties of the IDPs and the meteorites are likely to provide significant constraints on the physical properties of the meteors (see Flynn, 1999) as well as their asteroidal or cometary parent bodies.

2. Grain and Bulk Densities of Meteorites

Over the past decade a number of groups have reported measurements of the density and the porosity of meteorites (Consolmagno et al., 1998; Flynn et al., 1999a). To infer porosity both the grain density and the bulk density are measured on the same sample. The “grain density” is measured as the ratio of the mass of the meteorite to the volume occupied by the grains. The “grain volume” is typically measured using a He-pycnometer, which determines the volume of a sample that is impervious to He. The “bulk density” is the mass divided by the volume bounded by the external surface. For block-shaped samples this volume can be determined by geometrical measurements. However, many meteorites are quite rare, so these samples are not available for destructive analysis. Consolmagno et al. (1998) developed a non-destructive technique that uses a modified Archimedian method to determine the bulk volume. They replaced the water by freely flowing glass or plastic spheres, so they can determine the bulk volume without contamination of the meteorite (Consolmagno et al., 1998). The difference between the measured grain volume and the measured bulk volume is the volume of the pore space.

Britt and Consolmagno (2003) reviewed the density and porosity measurements on anhydrous and hydrated stone meteorites that have been obtained by several groups: including their own work, that of Flynn et al. (1999a), measurements on Antarctic meteorites by researchers at the National Institute for Polar Research in Japan, and almost 500 samples measured at the Geological Survey of Finland. All the ordinary chondrites (OCs) included in their review have grain densities between 3.25 and 3.80 gm/cc (Britt and Consolmagno, 2003). This is consistent with the density range expected for the major minerals known to be present in these meteorites. Further, the grain densities show the expected trend, an average grain density that increases with increasing metal content. The LL, or very low metal, ordinary chondrite meteorites have the lowest grain density (a mean of 3.48 ± 0.08 gm/cc), while the H, or high metal, ordinary chondrite meteorites have the highest grain density (3.64 ± 0.12 gm/cc), and the L, or low metal, ordinary chondrite meteorites have an intermediate grain density (3.51 ± 0.11 gm/cc). All of the carbonaceous chondrites that are dominated by anhydrous minerals (CV, CO, CH, and CK types) have a similar range of grain densities, with Britt and Consolmagno (2003) reporting mean grain densities of 3.48 ± 0.09 gm/cc for the CV meteorites, 3.48 ± 0.27 gm/cc for the CO meteorites, 3.44 gm/cc (with no error specified because of the small number of samples measured) for the CH meteorites, and 3.47 ± 0.02 gm/cc for the CK meteorites. These values are consistent with the grain densities of anhydrous silicates that dominate the mineralogy of these types of meteorites. The carbonaceous meteorites that show significant evidence of hydration (CI, CM and CR types) have much lower grain densities, with Britt and

Consolmagno (2003) reporting a mean of 2.26 ± 0.08 gm/cc for the CI meteorites, 2.71 ± 0.11 gm/cc for the CM meteorites, and 3.23 ± 0.28 gm/cc for the CR meteorites, reflecting the lower density of the phyllosilicate minerals that dominate their fabric.

The lowest bulk density reported for an anhydrous meteorite is 2.38 gm/cc for the LL ordinary chondrite Y-75258 (Britt and Consolmagno, 2003). This meteorite has a measured porosity of 33% (Britt and Consolmagno, 2003). Most of the unweathered ordinary chondrites have porosities of ~10% while many anhydrous carbonaceous chondrites have porosities of ~20% (Flynn et al., 1999a).

The lowest bulk density reported by Consolmagno et al. (1998) is 1.5 ± 0.2 gm/cc measured on a large (~47 gram) sample of the hydrated CI carbonaceous chondrite Orgueil. This meteorite has a porosity of 35%. Brown et al. (2002) estimate the pre-atmospheric porosity of Tagish Lake meteorite, a hydrated carbonaceous chondrite, to have been between 37% and 58%.

Some meteorites, called “finds,” have been exposed to terrestrial alteration because they were discovered on the ground some time after they fell to Earth. The weathered chondritic meteorites have much lower porosities, leading Consolmagno et al. (1998) to suggest that the effect of terrestrial weathering is to fill the pores of these meteorites with weathering products. The weathering of meteorite finds is characterized by the degree of oxidization of the metal and the degree of hydration of initially anhydrous silicates. The weathering scale ranges from “W0,” for meteorites that show no visible oxidation of metal or sulfide but may show a limonitic staining in transmitted light, through “W6,” for meteorites that exhibit massive replacement of silicates by clay minerals and oxides. (This weathering scale is described in detail by Wlotzka (1993)). Three of the ordinary chondrite meteorites found in the Sahara, Hammadah al Hamra 136 (classified as a W2), Hammadah al Hamra 072 (classified as W1), and Acfer 132 (classified as W1), show some minimal evidence of terrestrial weathering, but have low porosity (see Table I), suggesting that the filling of cracks occurs early in the terrestrial weathering sequence.

To determine the type(s) of porosity, Flynn et al. (2000) performed Computed Microtomography (CMT) measurements on stone meteorites. These results show that the stone meteorites exhibit three distinct types of porosity on the microscale:

- cracks
- vugs, and,
- gaps or low density regions separating chondrules from matrix.

The most common type of porosity in meteorites is cracks, including fractures induced by shocks experienced in cratering and disruption experienced by the parent body. Vugs occur less often, but they are the dominant type of porosity in some meteorites such as the L5 OC Mt. Tazewait.

TABLE I
Physical properties of meteorites

Sample (cm)	Length	Porosity (%)	Longitudinal velocity (m/s)	Shear velocity (m/s)	Elastic modulus (kN/mm ²)	Shear modulus (kN/mm ²)
Terrestrial samples						
Rhyolite	6.7		5888			
Rhyolite	1.7		5743			
Compact meteorites						
Gibeon (IVA Iron)	1.5		6260			
Richfield (LL3.7)	2.4	1.0 ± 0.7	5110	2450	52	19
H. al H.* 136 (L6)	3.3	0.3 ± 1.0	6382			
H. al. H.* 071 (L6)	3.0	1.0 ± 0.2	5118			
Possibly porous meteorite						
Acfer 132 (H6)	3.0	4.0 ± 7.0	3529			
Porous meteorites						
Axtell (CV3)	2.8	19.0 ± 0.5	4020	2330	38	15
Mt. Tazerzait (L5)	2.1	17.0 ± 1.0	2930	1870	23	10
repeat	2.1	17.0 ± 1.0	3014			
Bjurbole (L/LL4)	3.7	20.0 ± 2.0	1130			
repeat	3.7	20.0 ± 2.0	1030			
Bjurbole (L/LL4)	2.1		1180			
Saratov (L4)	3.0		2357			
Saratov (L4) w/crack	1.8	13.0 ± 2.0	1320			

All meteorite classifications are from Grady (2000).

* H. al H. = Hammadah al Hamra.

Chondrules are frequently surrounded by a rim of fine-grained material, which is compositionally similar to the matrix (described in Metzler and Bischoff, 1996). Greshake et al. (2005) have noted that, in the case of the carbonaceous chondrite Tagish Lake, this rim has a lower bulk density than the matrix. These chondrule rims may be the low density regions around the chondrules that were detected by CMT.

Flynn et al. (2000) noted that in the CMT images of whole stones, the OC meteorite Gao exhibited a crack that cut the fusion crust. This indicates that either the crack postdated the emplacement of the fusion crust, which is produced during atmospheric deceleration, or the crack widened significantly after emplacement of the fusion crust. Thus, some of the cracks observed in meteorites are likely to result from terrestrial effects rather than reflecting the condition of the parent body.

Objects tend to break into their strongest subunits, thus minimizing the microporosity of the smaller pieces. This trend is evident in the Orgueil data (Consolmagno et al., 1998; Britt and Consolmagno, 2003), where the sample having the lowest bulk density (1.5 gm/cc) is the largest Orgueil sample measured, while the smaller Orgueil samples have much higher bulk densities (averaging 2.1 gm/cc). Because of this preferential fragmentation into the strongest subunits, we might expect that the bulk density of the parent asteroid would be significantly lower than that of a meteorite derived from that parent. However, the bulk density of the meteorites might be lower than that of small meteors derived from the same parent body.

Porosity is known to affect other physical properties of a rock, including the speed of sound, the thermal conductivity, the strength, and the response to impact cratering and disruption.

3. Speed of Sound, Elastic and Shear Moduli in Meteorites

Alexeyeva (1960) measured the longitudinal wave velocities in eight ordinary chondrite meteorites and the shear wave velocities in six ordinary chondrite meteorites. He reported longitudinal wave velocities ranging from 2050 to 4200 m/s, values substantially lower than the 5400 to 5600 m/s reported for compact terrestrial rocks. His shear wave velocities, ranging from 600 to 1220 m/s in the meteorites, were also lower than those of compact terrestrial rocks.

Flynn et al. (1999b) measured the longitudinal and shear wave velocities, the elastic modulus, and the shear modulus of several meteorites using a Geotron-Elektronik Ultrasonic Measuring System, which was designed to allow accurate measurements on very small samples. First, Flynn et al. (1999b) measured the longitudinal wave velocity in two samples of a fine-grained, terrestrial rhyolite, which is a silica-rich, porphyritic rock with phenocrysts of quartz and alkali feldspar in a glassy or cryptocrystalline groundmass. A 6.7 cm long rhyolite sample was measured, and then a second rhyolite sample that was only 1.7 cm long, comparable to the size of the meteorite samples, was measured. The longitudinal wave velocities measured on these two samples, 5890 and 5740 m/s, respectively, agreed to better than 3%, and are comparable to literature values for silica-rich rocks (Halliday and Resnick, 1988). They also measured a sample of the Gibeon iron meteorite, and obtained a longitudinal wave velocity of 6260 m/s, slightly higher than the literature value of 5940 m/s for man-made steel (Halliday and Resnick, 1988). These results confirm the ability Geotron-Elektronik instrument to measure the longitudinal wave velocity on samples as small as ~2 cm in length.

Flynn et al. (1999b) measured the porosity and the longitudinal wave velocity a total of 10 samples from eight different stone meteorites, and they

measured the porosities of eight of these samples as well. These results are given in Table I. Of the four finds, three – Richfield, Hammadah al Hamra 136, and Hammadah al Hamra 071 – have very low porosities, indicative of significant terrestrial weathering. These three meteorites have longitudinal wave velocities ranging from 5110 to 6382 m/s, comparable to compact terrestrial rocks. The Acfer 132 sample, which is also a find, may exhibit some porosity (measured porosity = $4 \pm 7\%$). This sample has a somewhat lower longitudinal wave velocity (3529 m/s). The four meteorites that show significant porosity – Axtell, Mt. Tazerzeit, Bjurbole, and Saratov – have longitudinal wave velocities ranging from 1030 to 4020 m/s. These values are comparable to the longitudinal wave velocities reported by Alexeyeva (1960) and they are significantly lower than the values for compact terrestrial silicate rocks, including the rhyolite measured by Flynn et al. (1999b) and granite, with a sound speed of ~ 6000 m/s (Halliday and Resnick, 1988). The meteorite values are compared to literature values for brick, concrete, terrestrial basalt, and terrestrial rhyolite in Figure 1.

Bjurbole and Saratov are both extremely friable meteorites, which easily shed material. These two meteorites have the lowest longitudinal wave velocities of the group measured by Flynn et al. (1999b).

Generally, the longitudinal wave velocity and the thermal conductivity are correlated. Thus, it seems likely that the thermal conductivities of the meteors and their parent bodies are also significantly lower than the thermal conductivities of compact terrestrial rocks.

Flynn et al. (1999b) also measured the shear wave velocities on three meteorite samples – Richfield, Axtell, and Mt. Tazerzait. They found values ranging from 1870 to 2450 m/s (see Table I), somewhat higher than the values reported by Alexeyeva (1960) for six other ordinary chondrites, but lower than the values for compact terrestrial rocks.

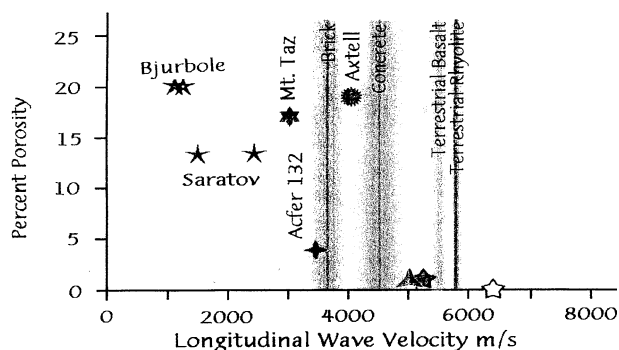


Figure 1. Comparison of the longitudinal wave velocity in chondritic meteorites with that of brick, concrete, terrestrial basalt and terrestrial rhyolite.

The elastic and shear moduli were also measured for these three meteorites (Flynn et al., 1999b). While Richfield has an elastic modulus of 52 kN/mm², which is comparable to that of terrestrial granite (~50 kN/mm²), the shear moduli for Axtel and Mt. Tazerzait, 23 and 38 kN/mm², respectively, are closer to the value for concrete (~20 kN/mm²).

4. The Atmospheric Filter Effect

The Earth's atmosphere acts as a filter, causing meteorites that have low physical strength (possibly resulting from high porosity) to break up due to the dynamic pressure they experience during deceleration. Fragments of the Tagish Lake meteorite are reported to have a bulk porosity of ~ 40% (Brown et al., 2000), but Tagish Lake was collected from a strewn field containing thousands of small pieces, indicating that the original meteorite was too weak to survive entry intact.

Because they decelerate much higher up in the atmosphere, where the atmospheric density is much lower, the IDPs experience significantly lower dynamic pressure than do the meteorites during atmospheric deceleration. Thus, the density and porosity of the IDPs may provide more realistic indications of the density and porosity of the meteors.

5. Interplanetary Dust Particles

The interplanetary dust particles are generally classified as either anhydrous, which means they are dominated by olivine, pyroxene, and glass, or hydrated, which means they are dominated by phyllosilicates, generally smectite or serpentine. Intermediate type IDPs, consisting of a mixture of anhydrous grains and phyllosilicates are also found. Many of the anhydrous IDPs are porous aggregates of thousands of sub-micron grains. The individual mineral grains appear to be held together by a carbonaceous "glue." The pore spaces in these anhydrous IDPs can easily be seen in SEM images of the surface, and the porosity is even more obvious in TEM images of ultramicrotome sections (as shown in Figure 2). Mackinnon et al. (1987) and Rietmeijer (1993) have both reported porosities in ultramicrotome thin-sections of IDPs as high as 90%. The hydrated IDPs are generally much more compact than the anhydrous IDPs.

Fraundorf et al. (1982a) determined the density of 7 IDPs, weighing each particle using the deflection of a quartz-fiber beam and determining the particle volume using a series of SEM images taken at a variety of angles. Flynn and Sutton (1988) and Zolensky et al. (1989) inferred the masses of 16

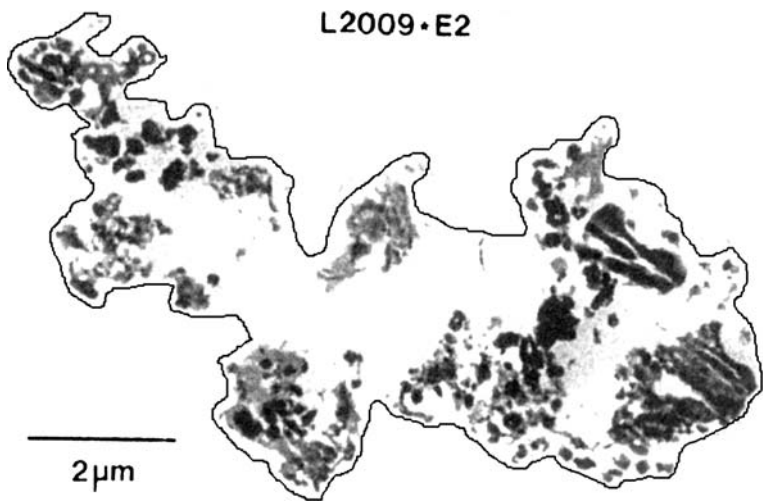


Figure 2. Transmission Electron Microscope (TEM) image of a single ultramicrotome slice, ~80 nanometers thick, from a highly-porous, chondritic aggregate interplanetary dust particle named L2009•E2. The black line indicates the approximate external boundary of the particle in this ultramicrotome section. The dark regions are electron absorbing material while the bright areas are either voids or material of extremely low density. (TEM image from L. P. Keller.)

IDPs from the measured Fe-content of each particle, and determined the volumes using an optical microscope.

The density distribution for 23 IDPs measured by the three groups was summarized by Flynn and Sutton (1991). The distribution is bimodal (as shown in Figure 3), with peaks at 0.6 and 1.9 gm/cc. The lower density peak most likely contains mostly the porous, anhydrous IDPs, while the more compact, hydrated IDPs are likely to be found in the higher density peak. The lowest measured IDP density is close to the very low density of 0.1 gm/cc inferred for some radar meteors (Verniani, 1964).

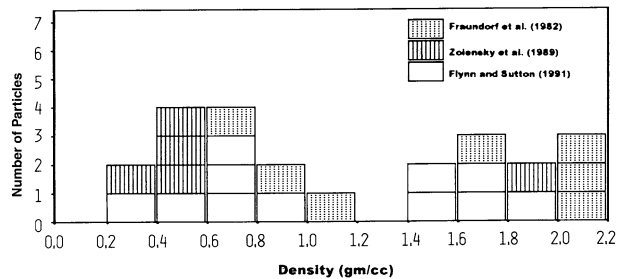


Figure 3. Interplanetary dust particle density distribution, combining data from Fraundorf et al. (1982a), Flynn and Sutton (1988), and Zolensky et al. (1989) (adapted from Flynn and Sutton, 1991).

Fraundorf et al. (1982b) suggested that the porous, anhydrous IDPs might be too weak to be self-supporting in the gravity of a large parent body. They suggested the pore space might have been filled by ices on the parent body, increasing the compressive strength of the material. However, even the porous, anhydrous IDPs appear to be quite strong when touched by the needles used to transfer the IDPs for analysis. It is not clear that the anhydrous IDPs are too porous to be self-supporting under gravity in an asteroid-size body. Silica aerogel can be manufactured with densities < 20 mg/cc, which corresponds to a porosity $> 99.8\%$. Blocks of this low-density silica aerogel can support more than 1000 times their own weight, thus a self-supporting column of this aerogel can be tens of meters high in Earth gravity, and kilometers high in the low self-gravity of a parent body. Thus, relatively large bodies composed of porous, anhydrous IDPs might be self supporting, even without ice filling the pore structure.

6. Response to Impact Cratering and Disruption

Hypervelocity cratering experiments demonstrate that porous targets require more energy for disruption than compact, non-porous targets (see e.g., Love et al., 1993). To investigate this further, Flynn and Durda (2004) performed impact disruption experiments on eight different anhydrous chondritic meteorites – seven ordinary chondrites, including Saratov (a very friable ordinary chondrite) and the Allende (CV3) carbonaceous chondrite.

The extent of the destruction in a collision is frequently characterized by the ratio of the mass of the largest fragment produced in the collision (M_L) to the mass of the target (M_T). This parameter, M_L/M_T , is 1 for a perfect rebound in which the target emerges unaltered. An M_L/M_T value of 0.5 is generally taken as the boundary between cratering events and catastrophic disruption (Fujiwara et al., 1989), with M_L/M_T ranging from 0.5 to 1 for cratering events, and $M_L/M_T < 0.5$ for catastrophic disruption. Plots of M_L/M_T versus the “specific impact energy” (i.e., the kinetic energy of the impactor per unit target mass) generally show a power-law trend in laboratory impact experiments on many terrestrial materials. The energy required disrupt the target material such that the largest fragment has 50% of the mass of the target (a parameter called Q_D^*) can be derived from the slope of this power-law (as discussed in Fujiwara et al., 1989). A least-squares fit to the data gave a value of 1419 J/kg for Q_D^* for the ordinary chondrite meteorites (Flynn and Durda, 2004), which are dominated by anhydrous minerals. Both the very friable OC Saratov and the carbonaceous chondrite Allende plotted within the field of data defined by the other 6 OCs (see Flynn and Durda, 2004). This value of Q_D^* is about double the value of ~ 700 to 800 J/kg reported for laboratory experiments on glass and basalt (Fujiwara et al., 1989), which indicates that at the size scale of ~ 100 g targets

the ordinary chondrite meteorites require more impact energy per unit mass to produce the same degree of disruption than is required for the glass and basalt samples.

This result can be understood by noting that if the target is porous some of the kinetic energy of the impactor is dissipated by compressing the target, and this energy is unavailable to disrupt the target. Thus, porous asteroids are likely to require more energy to produce the same degree of disruption than non-porous asteroids. Since the porosity data tabulated by Britt and Consolmagno (2003) indicates that all unweathered stone meteorites, both anhydrous and hydrated, exhibit significant porosity, most (or all) stone asteroids are likely to be porous, and, thus, they are likely to require more energy for disruption than non-porous rocks of similar mineralogy.

A significant fraction of the carbonaceous chondrite meteorites are hydrated, and some of the C-, P-, and D-type asteroids show evidence for hydration in their reflection spectra. Hydrated meteorites and their parent asteroids are likely to respond differently to impact cratering and disruption than do the anhydrous objects. However, most disruption experiments on natural rock targets have concentrated on anhydrous rocks, such as unweathered basalts and ordinary chondrite meteorites. Tomeoka et al. (2003) disrupted a small target of Murchison (CM2), a hydrated carbonaceous meteorite, and compared the result to their disruption of Allende (CV3), an anhydrous carbonaceous meteorite. They found that Murchison disrupted far more easily than Allende, producing much more fine-grained material when the two targets were disrupted under the same conditions.

For comparison with the anhydrous basalt targets previously disrupted (Durda and Flynn, 1999), Flynn and Durda (2005) disrupted three targets of "greenstone," a basaltic rock in which the olivine and peridotite that made up the fresh rock have been metamorphosed by high pressure and warm fluids into green minerals including epidote, actinolite or chlorite. A least-squares fit to the greenstone data yields a Q_D^* value of only 567 J/kg, indicating that these greenstone targets have a lower threshold collisional specific energy (Q_D^*) than either the anhydrous meteorites (Flynn and Durda, 2004) or the terrestrial glass and basalt (Fujiwara et al., 1989).

7. Conclusions

The anhydrous and the hydrated chondritic stone meteorites that have not been altered by terrestrial weathering all have significant porosity, ranging from 5% to 40%. The hydrated IDPs also exhibit significant porosity, while the anhydrous IDPs generally have even higher porosities, some as high as 90%. These results suggest that the stone meteors are likely to be highly porous objects. The most common type of porosity in the meteorites is

cracks. These cracks are likely to promote fragmentation during atmospheric deceleration by allowing the pressure from air drag or internal pressure that arises from heating to tear the object into pieces. Thus, meteors are likely to be more prone to fragmentation than compact (i.e., low porosity) terrestrial rocks. However, the presence of significant porosity increases the energy that must be delivered to a given mass of material in order to produce impact fragmentation, because some of the energy delivered by the impactor goes into compressing the target rather than fragmentation. Thus the meteors, and their parent bodies, are likely to be less prone to the production of fragments by impact cratering or disruption than are the compact terrestrial rocks. The porous, unweathered meteorite samples all have significantly lower longitudinal wave velocities than are measured in compact terrestrial rocks. Since longitudinal wave velocities and thermal conductivity are usually correlated, the meteors are likely to have lower thermal conductivities than compact terrestrial rocks as well.

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SPECTROSCOPY OF A GEMINID FIREBALL: ITS SIMILARITY TO COMETARY METEORIODS AND THE NATURE OF ITS PARENT BODY

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Abstract. A detailed analysis of a photographic spectrum of a Geminid fireball obtained in December 14, 1961 at the Ondřejov Observatory is presented. We have computed a synthetic spectrum for the fireball and compared it with the observed spectrum assuming chemical equilibrium in the meteor head. In this way we have determined relative chemical abundances in meteor vapors. Comparing the relative chemical abundances of this Geminid meteoroid with those obtained from meteoroids associated with comets 55P/Tempel-Tuttle and 109P/Swift-Tuttle we found no significant chemical differences in main rock-forming elements. Despite of this similarity, the deepest penetration of the Geminid meteoroids and their ability to reach high rotation rates in space without fragmentation suggest that thermal processing is affecting their physical properties. We suggest that as consequence of space weathering a high-strength envelope is produced around these particles. In this picture, heating processes of the mineral phases could result in the peculiar properties observed during atmospheric entry of the Geminid meteoroids, especially their strength, which is evidenced by its resistance to ablation. Finally, although one meteoroid cannot be obviously considered as representative of the composition of its parent body, we conclude that 3200 Phaethon is able to produce millimetre-size debris nearly chondritic in composition, but the measured slight overabundance of Na would support a cometary origin for this body.

Keywords: Asteroid 3200 Phaethon, fireball, Geminid, meteor spectrum, meteoroid

1. Introduction

3200 Phaethon was discovered by the Infrared Astronomical Satellite (IRAS) in 1983 (Green, 1983). Since then, the nature of this Apollo object has been debated vigorously: is it an extinct comet or an asteroid? Initially, some authors classified 3200 Phaethon as a S-type asteroid in basis to reflectance spectroscopy (Cochran and Baker, 1984; Belton et al., 1985). However Veeder et al. (1984) did not confirm these first results, and remarked that the object was extremely blue. Higher resolution spectra obtained with the near-infrared spectrograph KSPEC revealed a dust continuum similar to the reported for several comets like 2060 Chiron and P/Schwassmann-Wachmann 1 (Dumas et al., 1998), and no evidence of cometary degassing has been obtained up to now (Chamberlin et al., 1996; Campins et al., 1999). The surface properties of minor bodies can be modified by space weathering and/or due to the presence of regolith. Both effects make extremely difficult the detection of extinct cometary nuclei although the possible cometary nature of some asteroids has been suggested and is currently debated (Flynn, 1989; Lodders and Osborne, 1999). The presence of a dense meteoroid shower associated clearly with Phaethon has been seen as a good example of how Meteor Science can bring interesting information about Solar System bodies (Whipple, 1983; Hunt et al., 1985; Williams and Wu, 1993). In fact the extraordinary similarity between Phaethon's orbit and Geminid meteoroids is difficult to controvert (Williams and Wu, 1993), being the densest known annual meteoroid stream intercepting the Earth. Phaethon's meteoroids intercept the Earth's orbit in December and their radiant is projected on the constellation of Gemini. The Geminid meteor shower reaches a maximum zenith hourly rate in excess of 100 around December 13 each year. Usually this shower displays activity during 10 days having the unusual property that the peak activity occurs only a day or so from the end of the display. Gustafson (1989) concluded that the conditions for meteoroid transference from Phaethon to the Geminid stream are those expected from cometary activity. Later Williams and Wu (1993) deduced that meteoroids ejected from Phaethon more than 1000 years ago could have evolved under planetary perturbations and radiation pressure into Earth-crossing orbits. They confirmed that Phaethon is the largest remnant of the parent body of the Geminid stream, but they were unable to shed light on whether Phaethon released these meteoroids under a cometary or asteroidal behaviour. Despite this, cometary ejection seems a better approximation when comparing the model and the observed orbital and physical properties of the meteoroids (Halliday, 1988). The Geminid meteoroid stream is rather unusual in having a short orbital period of 1.57 years and a semimajor axis of only 1.35 A.U. These orbital characteristics confer on this stream a relative stability, free

from important gravitational effects from the outer planets. We analyse here one grating spectrum of a Geminid fireball registered in the Ondřejov Observatory (Czech Republic) in 1961. Meteor spectra from this stream are rare because the amount of meteoroids with masses producing luminous meteors to be imaged by spectrographs is more restricted than in the case of other meteor showers. Using the method developed by Borovička (1993) we have derived the relative chemical abundances from the meteor column in order to compare this meteoroid to others coming from streams associated to comets. Some interesting similitudes with cometary meteor spectra are found, thus supporting the cometary nature for 3200 Phaethon.

2. Observations and Data Reduction

The Geminid spectrum (GEM) was obtained on 14 December 1961 at the Ondřejov Observatory (Czech Republic) at 2h47m34s UTC. The trajectory data and orbital elements compared to the average Geminid stream and the Phaethon parent body are given in Tables I and II. The dispersing element used was a diffraction grating with 600 grooves/mm. The camera focal length was 360 mm and the focal ratio 1:4.5. The spectrograph was equipped with a 18 × 24 cm AGFA 100 photographic plate. The original spectral plate was measured in detail, dividing the fireball in different scanning paths for a same height on the atmosphere, using a two-axis microdensitometer at the Ondřejov Observatory. The camera plate was also scanned along the diffraction hyperbola since long meteor paths can be out of the optical axis of the camera (Ceplecha, 1961). In order to obtain such detailed scanning, the microdensitometer included a rotation slit for keeping the measured signal

TABLE I
Trajectory of the Geminid fireball

Trajectory data	
Beginning height (km)	96.3
Ending height (km)	56.7
Absolute panchromatic magnitude	(−5.1)
Initial velocity (km/s)	37.8
Ending velocity (km/s)	26.8
Geocentric Radiant (1950.00)	$\alpha = 113.82 \pm 0.28^\circ$ $\delta + 33.54 \pm 0.11^\circ$
Zenithal angle (z_R)	24.4°

TABLE II
Main orbital elements of the meteoroid that produced the GEM fireball compared with the averaged Geminid stream and the 1983TB Phaethon parent body

Orbital elements (1950.00)	GEM	Geminids	(3200) Phaethon
Semimajor axis (A.U)	1.674 ± 0.036	1.36	1.27133
Eccentricity	0.9168 ± 0.0020	0.896	0.890156
Perihelion distance (U.A)	0.1394 ± 0.0022	0.142	0.139844
Argument of perihelion (°)	322.63 ± 0.39	324.3	321.8207
Longitude of the Ascending Node (°)	262.7347 ± 0.0007	261.0	265.5874
Inclination (°)	28.51 ± 0.44	23.6	22.102

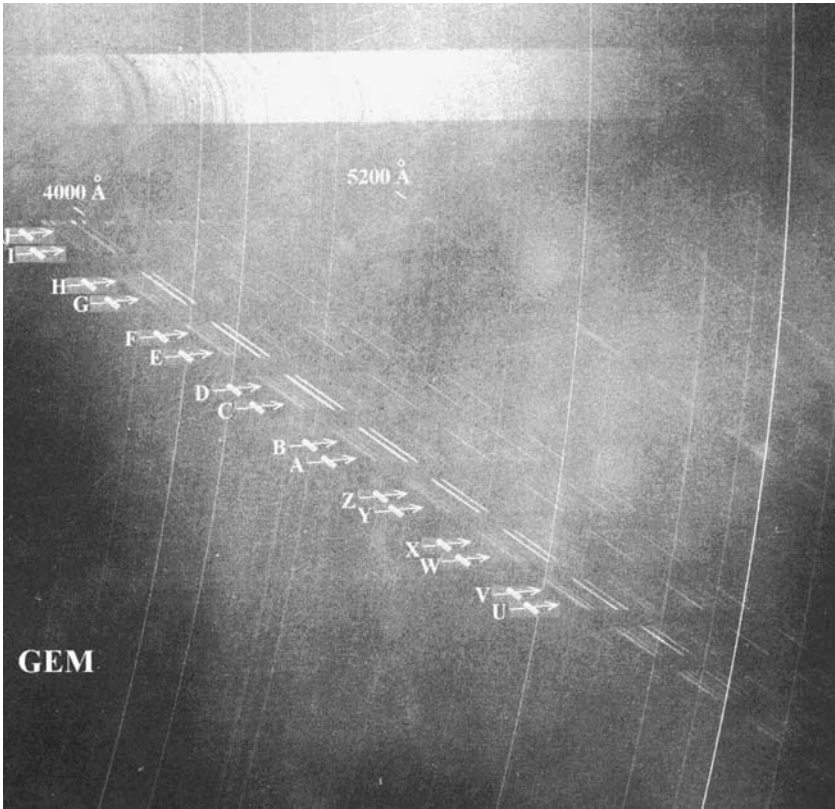


Figure 1. The original spectrograph contained the spectrum of the Polaris star (on top in the second order). The Geminid spectrum appears below showing the different scanned paths (segments) taken in order to determine the physical parameters and chemical abundances along the path.

window parallel to the meteor path. The slit dimensions were adapted to the apparent size of the brightest lines. The spectrum was scanned twice per segment. The exact location of the scans was marked on photographs as it is shown in the GEM spectrum (Figure 1). Letters named in growing and decreasing order designed scans. All the spectral analyses and scans are available in Trigo-Rodríguez (2002). The photometric signal was carefully calibrated according to the relative spectral sensitivity of the spectrograph. The wavelength scale for each spectrum was determined by means of known lines in the spectrum (Borovička, 1993). Plate sensitivity at each wavelength was obtained by studying the bright and detailed spectra of the Polaris star that was recorded in the same plate as the spectrum GEM as was previously described in Trigo-Rodríguez et al. (2003). Briefly, the linear part of the characteristic curve of the plate GEM was constructed by scanning the zero order spectra of all stars recorded, excluding the red and variable stars. Then the first and second order of the Polaris spectrum was scanned. The wavelengths scale was determined by means of known emission and absorption lines in the stellar spectrum. In order to relate the instrumental lengths to wavelengths, a polynomial adjust of degree 3 was used. The real energy distribution of the Polaris spectrum was calculated using the Kurucz (1991)

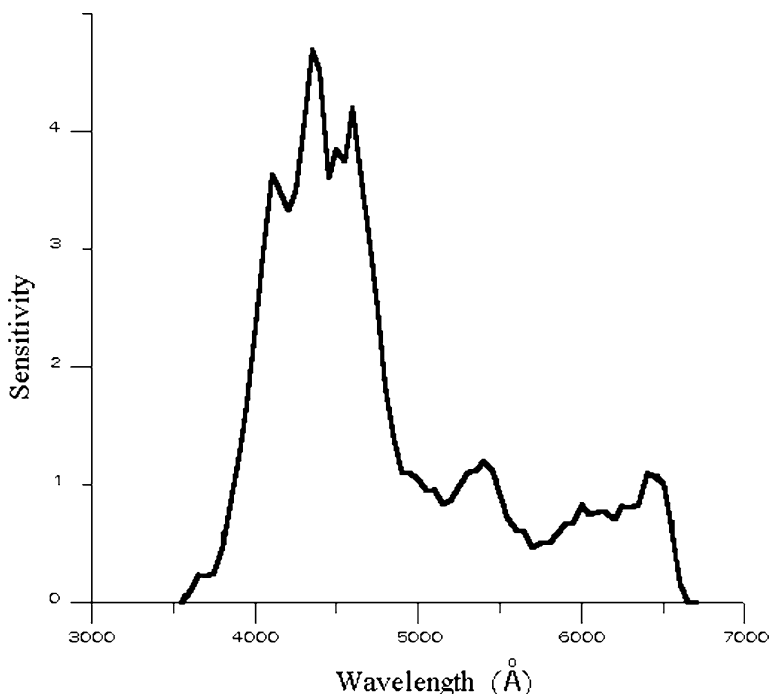


Figure 2. Spectral sensitivity of the AGFA 100 photographic plate. Adapted from Trigo-Rodríguez et al. (2003).

atmosphere models implemented within the DIPSO package of the Starlink software collection (Howart et al., 1996) such as is described in more details in Trigo-Rodríguez (2002) and Trigo-Rodríguez et al., (2003). Such spectrum model of Polaris was compared with the first and second order spectra recorded on the original plate, and transformed into the relative spectral flux by means of the characteristic curve. The ratio of both yielded the relative spectral sensitivity function that provides us the plate response for each wavelength (Figure 2).

The GEM spectrum has a resolution of $78 \text{ \AA/mm}$ although the low luminosity of the fireball (approximately $M_p = -5.1$ at the maximum light) makes difficult to identify lines of minor chemical elements on the plate. Despite of this, the analysis allowed us to determine the relative abundance of Ca, Mn, Fe, Mg, Na and Cr.

3. Physical Analysis and Relative Chemical Abundances

The GEM spectrum was analysed at the scanning paths marked in Figure 1. To obtain the relative chemical composition of the Geminid meteoroid we used the geometrical model of the meteor developed by Borovička (1993). The radiating volume is treated as a prism with square base and elongated in the direction of the meteor flight following the procedure described in Trigo-Rodríguez et al. (2003). Assuming thermal equilibrium, the brightness of the spectral lines is computed by adjusting four parameters: temperature (T), the column density of atoms (N), the damping constant (γ) and the surface area (P). We used the software developed by Borovička (1993) that uses the least square method in order to reconstruct a synthetic spectrum by direct comparison with the Geminid spectrum in the different scanned segments of the trajectory (see e.g. Figure 3). When the best fit is reached, the determination of the four previously mentioned physical parameters is completed. As most lines in the spectrum are of neutral iron, consequently Fe I is taken as a reference element to adjust the intensity of lines and temperature. One time T , γ and P have been estimated the software allows changing the column density (N) of any element. In order to obtain the chemical composition in the meteor column is fundamental to consider the degree of ionization of the different elements, taking into account the ratio of neutral, singly and doubly ionized atoms given by the Saha equation (Borovička, 1993; 1994a, b). Following this procedure the effective excitation temperature of the main component gas was determined with an estimated precision of $\pm 100 \text{ K}$. The high temperature component of the spectrum was weak, but can be adjusted to a temperature of $9500 \pm 500 \text{ K}$.

The temperature of the main component was found to be typically between 4200 and 4300 K, but a short peak in J and L segments was reached

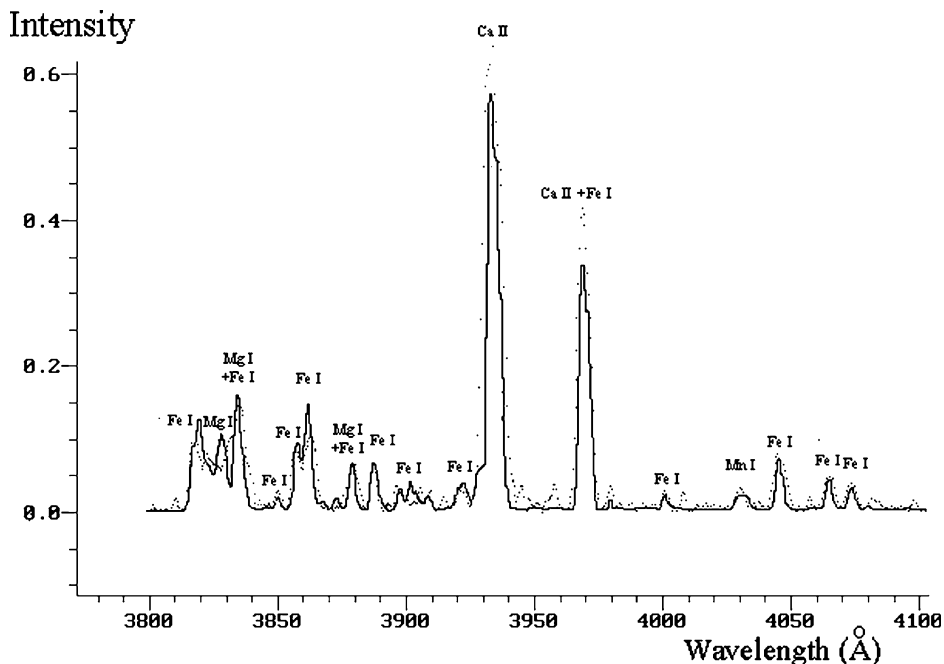


Figure 3. Observed spectrum (dotted line) and the synthetic one (continuous line) obtained from the determination of physical parameters following the method explained in the text. This spectrum corresponds to segment d in the interval of wavelength 3800–4100 Å where the main elements contributing to the lines are identified. The synthetic spectrum is the sum of lines coming from the main and the second component, respectively at 4200 and 9500 K.

with a maximum of 4500 K. Such range of temperatures is below the associated with the ablation column of higher velocity meteors such as Perseid and Leonid (Borovička and Betlem, 1997; Borovička and Jenniskens, 2000). The main differences between a Perseid and the Geminid spectrum are shown in Figure 4. In the brightest scanned segments (I, J and LL) the ratio of the mass ablation products involved in the production of both spectral components was estimated. In order to do this, we estimated the ratio of the number of iron atoms contributing to both components. We obtained in the brightest segments the mass ratio between the main component and the high temperature component to be 20. The contribution of the second component is lower in the beginning of the meteor where $m_1/m_2 \approx 50$ –100. It can be easily explained because the amount of ionised Fe is lower when the meteoroid goes through atmospheric layers where the density is lower and, consequently, the probability of a collision producing ionised products is also lower.

The temperature and chemical abundances relative to Fe for the different scanned segments are given in Table III. The abundance of Mg is between the expected for Interplanetary Dust Particles (IDPs) and for CI chondrites

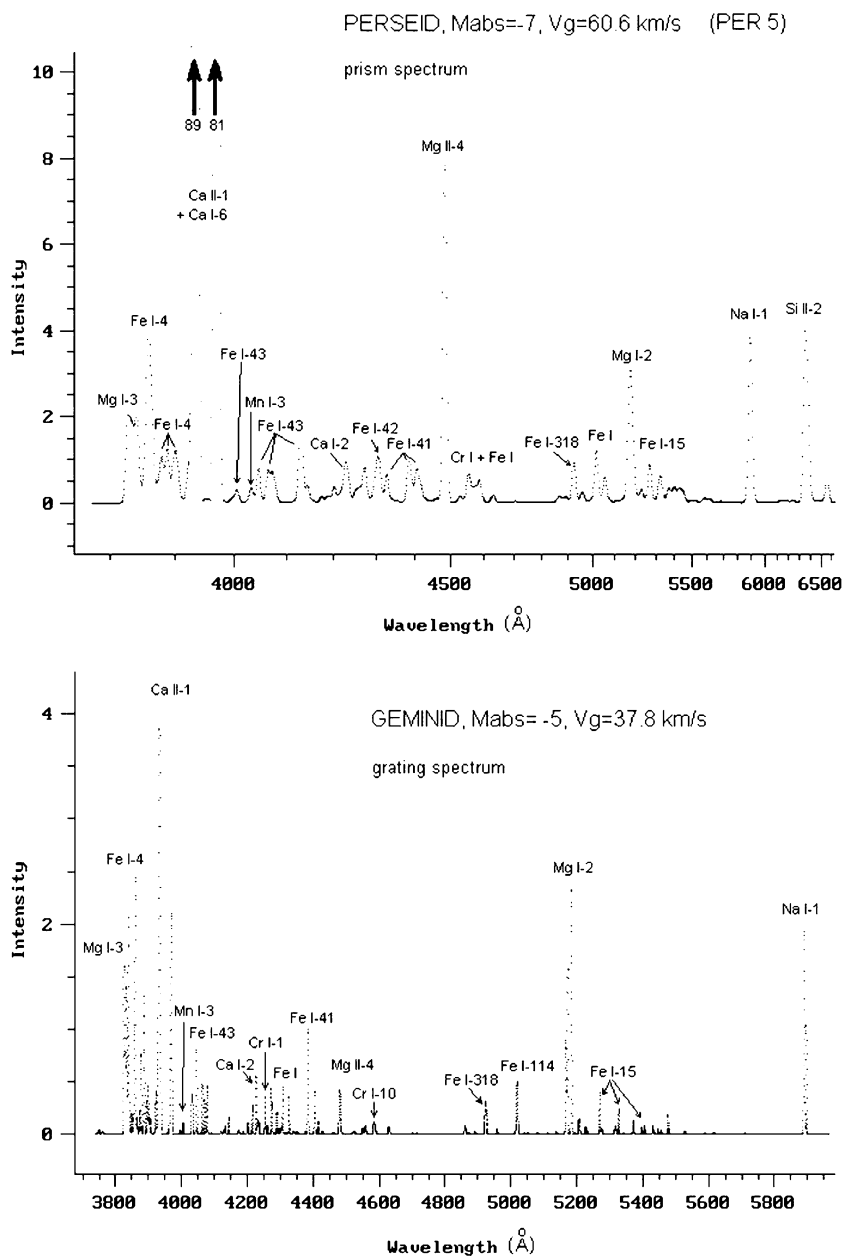


Figure 4. Comparison between the intensity of spectral lines of a Perseid fireball (PER 5) with the exhibited by the Geminid fireball in segment B. The lines belonging to the high temperature component are weak in the Geminid spectrum as a consequence of its lower geocentric velocity. Both spectra were analysed in (Trigo-Rodríguez, 2002).

TABLE III

Relative chemical abundances relative to Fe for the different segments analysed of the Geminid spectrum

Segment	Magnitude ± 1	$T \pm 100$ (K)	Ca ($\times 10^{-3}$)	Mn ($\times 10^{-4}$)	Mg	Na	Cr ($\times 10^{-4}$)
A	-4.6 ± 1.0	4200	22	78	1.21	0.09	43
B	-4.8	4200	25	76	1.06	0.10	100
C	-4.3	4200	34	47	1.07	0.13	53
D	-4.3	4200	7	31	1.21	0.07	52
E	-4.8	4200	6	46	1.05	0.07	50
F	-5.0	4200	7	16	0.94	0.14	55
G	-5.0	4300	26	63	1.09	0.09	106
H	-4.9	4300	8	34	1.29	0.13	121
I	-5.1	4300	21	49	0.96	0.13	112
J	-5.1	4500	33	82	1.16	0.12	166
Z	-4.9	4200	6	75	0.90	0.14	97
X	-4.7	4200	14	47	0.62	0.10	53
W	-4.3	4200	18	62	0.90	0.07	98
M	-5.0	4300	13	75	1.08	0.09	51
LL	-5.1	4300	15	50	1.14	0.21	59
L	-5.0	4400	28	83	1.16	0.16	115
Average	—	—	18 ± 9	49 ± 18	1.05 ± 0.16	0.12 ± 0.04	83 ± 36
CI	—	—	68	100	1.2	0.07	144
IDPs	—	—	76	238	1.35	0.08	190
P/Halley dust	—	—	120	95	1.92	0.19	170

For more details on the scanned segments see Figure 1. For comparison are given the typical abundances for CI chondrites, Interplanetary Dust Particles (IDPs) and 1P/Halley dust calculated relative to Fe from the original Rietmeijer and Nuth III (2000) data relative to Si.

(Table III). Mn and Cr are little below the expected for chondritic composition probably suggesting that both elements are not contributing completely to meteor light. Differences with 1P/Halley dust are easily explained because Giotto mass spectrometers detected only tiny particles that are not chondritic in composition (see e.g. Rietmeijer, 2002). The Ca abundance change along the trajectory, but its contribution to the meteor light is higher when the temperature increases. Finally, the measured Na abundance is similar to the obtained for other cometary meteoroids producing fireballs recorded with the same type of spectrograph than the present Geminid (Trigo-Rodríguez et al., 2003). In general, the Geminid meteoroid has abundances similar to other cometary meteoroids inside the range of chondritic meteorites and IDPs.

In this Geminid spectrum there is not evidence for FeO or other molecular bands contributing to meteor light. In any case other authors calculated that the contribution of these molecular bands can be important (Alexander and Love, 2001; Alexander et al., 2001; Flynn, 1991; McNeil et al., 2002; Murad, 2001). FeO has also been observed in persistent trails (Jenniskens et al., 2000). Future studies on the contribution of these molecular bands in the determination of chemical abundances are required.

4. Discussion

The mass of the meteoroid producing the GEM spectrum was estimated to be about 4 g (Trigo-Rodríguez et al., 2003). Assuming a chondritic density, this corresponds to a diameter of about 3 mm. Despite of this small size, the observed chemical abundances are typically chondritic (Table III).

The Ca behaviour along the trajectory deserves special discussion. The contribution of Ca to the meteor light increases as function of the temperature as is shown in Table III for the brightest segments (from G to LL). Trigo-Rodríguez et al. (2003) found a clear dependence between the Ca contribution to meteor spectra and the geocentric velocity. Ca is only moderately volatilised in high velocity meteoroids where the temperatures reached are higher than in GEM. The reason is that Ca is present in refractory mineral phases with highest resistance to volatilisation. Assuming that the GEM meteoroid had a chondritic abundance, less of a 25% of the Ca content would be contributing to produce light.

The derived Na abundance suggests that the particle's size is able to preserve mineral phases associated with this volatile element inside the meteoroid. In fact Trigo-Rodríguez et al. (2004) reported recently from meteor spectroscopy that cometary particles producing fireballs are overabundant in Na. Borovička et al. (1999) pointed out that small cometary particles suffer depletion in the Na content. Due to their higher surface-area/volume ratio, sodium-rich phases are more easily exposed to solar radiation heating and solar wind bombardment. Future spectroscopic observations of Geminid meteors and other cometary meteoroids may get insight into the importance of this depletion as function of meteoroid's size.

Cometary particles suffer degradation mainly by three processes: thermal, radiative and collisional (Stern, 2003). The averaged temperature for the Geminid meteoroids along their entire orbit is 226 K, being the highest of any known meteoroid stream intercepting the Earth (Beech et al., 2003). The deepest penetration of the Geminid meteoroids (Halliday, 1988) and their ability to reach high rotation rates without fragmentation suggest that thermal processing is affecting the physical properties of the Geminid meteoroids (Beech et al., 2003).

If the Geminid have a special ablation behaviour, but the chemical composition of the main chemical elements is similar to other cometary meteoroids, perhaps the different behaviour would be explained by the presence of an envelop surrounding the particles. There is no evidence to relate this wrap to organics but if this hypothesis is true, the study of Geminid meteors using high-sensitivity cameras working in the UV and IR would be an interesting astrobiological target. Other possibility would be that space weathering produced such envelope. It would happen from interaction of the particles by solar photons, by particles of the solar wind or by impacts with micrometeoroids. The degradation by radiation induced by photons and by the bombardment of charged particles of the solar wind is expected to be intense in the Geminid orbit. Especially solar and interstellar ultraviolet ($h\nu > 3$ eV) radiation is able to break bonds and induce substantially chemical alteration in cometary surfaces. This kind of radiation can produce significant degradation of the composition of cometary surfaces, promoting surface darkening and devolatilization progressively more severe with dosage, directly proportional to the Sun proximity (Greenberg, 1982; Thompson et al., 1987; Hudson and Moore, 2001). Because of their close proximity to the Sun, 3200 Phaethon experiences a high UV and solar cosmic ray surface dose. The effect of this radiation probably lead to the gradual conversion of the original water-dominated ice matrix to a complex dark surface by formation of long-chain organic polymers (Stern, 2003). In consequence, the higher strength observed in the surface of these meteoroids would be “delaying” the meteoroid ablation until such envelope disappear at the beginning of the trajectory. The main difference with the Na-rich matrix proposed for other cometary meteoroids (Trigo-Rodríguez and Llorca, 2004) is that, due to the particular orbit of the Geminid stream, thermal processing has removed the presence of volatile elements as Na in the processed outer region.

5. Conclusions

From the analysis of the Geminid fireball spectrum, we conclude the following:

- (i) The Geminid meteoroid had in general chondritic chemical abundances, but exhibiting a high content in Na characteristic of cometary meteoroids (Trigo-Rodríguez et al., 2004). Despite that Geminid meteoroids are affected by high temperatures in their orbits around the Sun, the analysed spectrum shows that volatile elements as Na can be still preserved inside millimetre-sized meteoroids.
- (ii) The depletion of Na and other volatile elements is clearly dependent of the particle's mass. Borovička et al. (1999) remarked that submillimeter cometary particles producing meteors in the video range suffer depletion

- in the Na content. Due to their higher surface-area/volume ratio, Na-rich phases are more easily exposed to solar radiation heating and solar wind bombardment, being the volatile phases depleted more efficiently.
- (iii) To explain the deepest penetration of the Geminid meteoroids and their ability to reach high rotation rates without fragmentation, Beech et al. (2003) suggested that thermal processing is affecting the physical properties of the Geminid meteoroids. If it is true, according to the chemical similitude between GEM and cometary meteoroids, we propose that an envelope compacted by space weathering would be covering the particles. Due to the presence of this high-strength outer region the ablation will occur little bit deeper in the atmosphere than the expected for lower-strength cometary particles.
- (iv) Although one meteoroid cannot be obviously considered as representative of the composition of its parent body, the chemical abundances deduced for the Geminid meteoroid support a chemical composition similar to that expected for cometary meteoroids. 3200 Phaethon is able to produce millimetre-size debris nearly chondritic in composition, but the slight Na overabundance would support a cometary origin for this body.

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CLASSICAL METEOR LIGHT CURVE MORPHOLOGY

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Abstract. We investigate the morphological variation of classical meteor light curves, under the constant velocity assumption, for a series of idealized atmospheric density profiles. We look specifically at the $t_{\text{rise}}/t_{\text{fall}}$ ratio, which compares the rise time to maximum brightness against the time to fall from maximum brightness. We demonstrate that for a classical meteoroid undergoing rapid ablation in an isothermal atmosphere that $t_{\text{rise}}/t_{\text{fall}} > 1$, indicating that all such light curves are late peaked. For a classical meteoroid ablating in a region over which the density is constant, $t_{\text{rise}}/t_{\text{fall}} \equiv 0$, and the light curve is necessarily downward concave in the height vs. intensity diagram. If ablation occurs over a region in which the density increases linearly with decreasing height, then $t_{\text{rise}}/t_{\text{fall}} = 1/(\sqrt{5} - 1) \approx 0.81$, indicative of an early peaked, near symmetric light curve.

Keywords: Ablation, atmospheres, meteoroids

1. Introduction

Classical meteoroid ablation is here defined as ablation proceeding under a constant velocity condition and under the assumption that meteoroids are structurally monolithic, spherical grains. We further assume that no fragmentation occurs during ablation. Given that these conditions are in place, we proceed to investigate the various light curve morphologies (that is the shape of the brightness profile, the end height and the height of maximum brightness) that result under the imposition of several idealized atmospheric density profiles.

The motivation behind this study follows from the recent acquisitions of abundant Leonid meteor light curve data (see e.g., Campbell et al., 2000; Koten and Borovicka, 2001; Beech and Murray, 2003). Indeed, the collective observations clearly indicate that Leonid meteor light curve profiles show a great variety in their form; from being early peaked, to symmetrical and even being late peaked. It is the origin of these various morphologies that we wish, ultimately, to understand. To begin this process of assimilation, we first investigate a series of light curve profiles that have been constructed with elementary (but not wholly unrealistic) atmospheric density profiles. We also

present expressions for light curve asymmetry by evaluating the ratio of the rise to and fall from maximum brightness times, $t_{\text{rise}}/t_{\text{fall}}$. In the case of the Leonids, the approximations outlined in the first paragraph of this section hold true to a reasonably good order of approximation. Indeed, even for the brightest (that is most massive) Leonid meteors no discernible decelerations have been measured (Spurny et al., 2000), and, in addition, bright flare events that are indicative of gross fragmentation, are not commonly observed in Leonid meteor light curves.

2. The Ablative Mass Loss Equation

We proceed by introducing the variables μ and U , such that $\mu = \eta m^{1/3}$ and $U = \varepsilon V^2$, where η and ε are constants, V is the meteoroid velocity and m is the meteoroid mass (the various constants are described in detail in Beech and Murray, 2003). Upon substitution of these terms into the standard ablation equations (see e.g., Bronshten, 1983), it can be shown that U is dimensionless and that μ has units corresponding to mass per unit area (Beech and Murray, 2003). Under the constant velocity approximation we then find that the classical mass loss equation reduces to $d\mu/d\psi = U$, where $d\psi = \rho(h) dh$, and where $\rho(h)$ accounts for the atmospheric density variation as a function of height h . The height variation of μ is therefore,

$$\mu(h) = \mu_0 + U \int \rho(h) dh, \quad (1)$$

where μ_0 is the initial mass per unit area and the integral is taken over the height range from h_0 , a beginning reference height, and $h < h_0$. Further, taking the energy radiated at optical wavelengths to be proportional to the kinetic energy of the ablated material, the intensity $I(h)$ will be $I(h) = I_0 \rho(h) \mu^2$, where I_0 is a constant. The form of the intensity equation indicates that it is the relative variation of μ and ρ with atmospheric height h that determines the morphology of the classical meteor light curve. In the sections below, we consider strictly analytic solutions to the intensity equation $I(h)$ under a variety of idealized model atmosphere approximations.

3. Isothermal Atmosphere

Under the isothermal atmosphere approximation the density variation is of the form $\rho(h) = \rho_0 \exp(-h/H)$, where H is an appropriately chosen scale height. Bronshten (1983) has shown that under the constant velocity condition the meteor intensity in an isothermal atmosphere will vary as $I = (27/4)$

$I_{\max} X (1 - X)^2$, where $I_{\max}$ is a constant, and $X = D\rho(h)$, where $D = (U \rho_0 h_0 / \mu_0)(H/h_0)$ is a constant related to the initial mass and velocity. The mass per unit area can further be shown, via Equation (1), to vary as $\mu = \mu_0(1 - X)$ under the isothermal atmosphere, constant velocity condition. With the above conditions in place we may establish the following theorem: *A classic meteor light curve will always be late peaked under the constant velocity, isothermal atmosphere condition irrespective of meteoroid composition, mass and initial velocity.* Briefly, the proof of this theorem follows by looking at the possible solutions to the cubic equation $X^3 - 2X^2 + X - K = 0$, where $K = (4/27)(I/I_{\max})$. First, the discriminant of the cubic equation is negative for all $0 \leq K < 4/27$, indicative of the existence of three real and distinct solutions to the equation. An inspection of the specific solutions to the cubic equation, for any given value of $0 \leq I/I_{\max} \leq 1$, indicates that we can always extract two real and distinct values of X such that $0 < X_1 < 1/3 < X_2 < 1$ are solutions to the cubic equation. The third solution X_3 need not concern here us since it is always greater than unity and this would imply that $\mu < 0$, which is unphysical. For each solution pair (X_1, X_2) we may construct the ratio of the rise to and fall from maximum brightness times. In order to do this we make use of the constant velocity condition and the fact that the rise time to maximum brightness will take place over a height range $h(X_1) - h_{\max}$, similarly, the fall time will encompass a travel distance of $h_{\max} - h(X_2)$, and that $h_{\max}$ occurs at $X = 1/3$. In this fashion we find $t_{\text{rise}}/t_{\text{fall}} = -\ln(3 X_1)/\ln(3 X_2) > 1$ thus, establishing the result that a classical light curve under the isothermal atmosphere approximation must always be late peaked. A sample of classical light curves produced under the isothermal atmosphere approximation is shown in Figure 1a.

4. Constant Density Region

In this highly idealized case we adopt a density variation of the form $\rho(h) = \rho_0 H(1 - h/h_0)$, where ρ_0 is a constant, h_0 is a reference height and $H(1 - h/h_0)$ is the Heaviside step function. We then find that for $x = h/h_0 \leq 1$ that $I(h) = I_{\max} [1 - G_C (1 - x)]^2$ where the constant $G_C = U \rho_0 h_0 / \mu_0 \geq 1$. In addition, we find that the end height, at which $\mu = 0$ is attained, is $h_E = h_0(1 - 1/G_C)$ and that the meteor trail length is $L = \mu_0/(U \rho_0)$. Furthermore, the form of the intensity equation dictates that $t_{\text{rise}}/t_{\text{fall}} \equiv 0$ because $h_{\max} \equiv h_0$. The intensity functionally varies as the atmospheric height squared, and presents, therefore, a downward convex profile in the height vs. intensity diagram. A series of example profiles are shown in Figure 1b. Beech and Hargrove (2004, submitted) discuss this model in a little more detail and also investigate the ‘physical’ implications of the $G_C = 1$ solution.

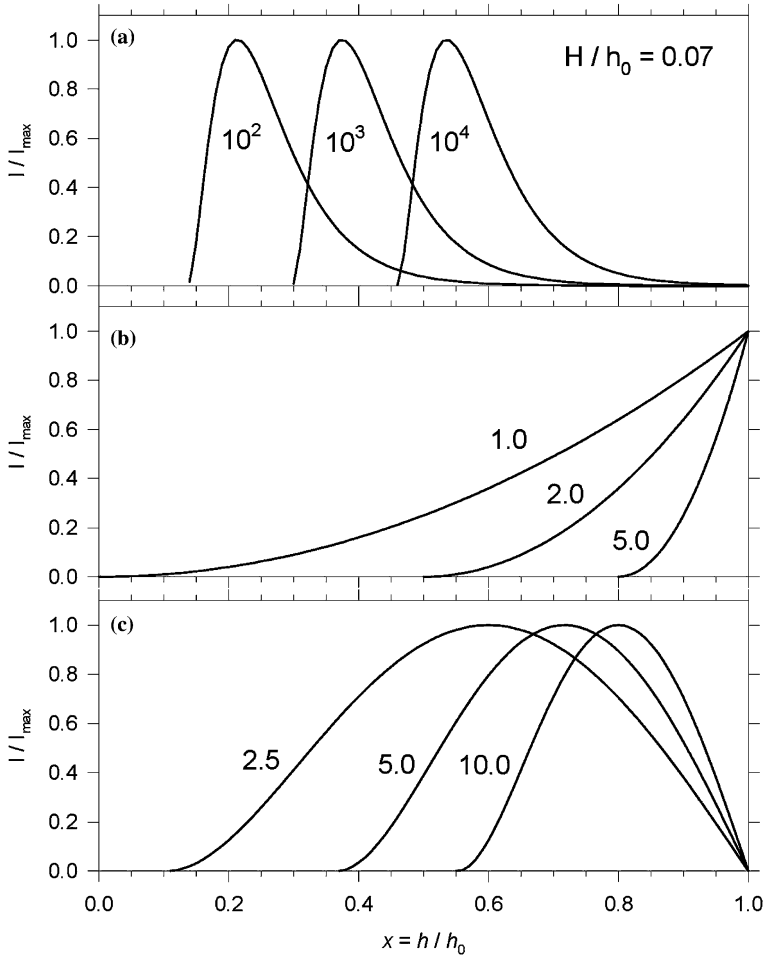


Figure 1. (a) A series of classical meteor light curves produced under the isothermal atmosphere approximation. The curves are labeled according to the value $G = U\rho_0 h_0/\mu_0$ and constructed under the assumption that $H/h_0 = 0.07$ corresponding to an imposed beginning height of $h_0 = 116$ km. For all such classical light curves $t_{\text{rise}}/t_{\text{fall}} > 1.0$. (b) Constant density atmosphere classical meteor light curves for $G_C = 1.0, 2.0$ and 5.0 . Note that the light curves have been normalized according to maximum brightness, that they are downward convex, and that they have a zero rise time to maximum. (c) Linear density atmosphere classical light curves for $G_L = 2.5, 5.0$ and 10.0 . Note that the light curves have been normalized to maximum brightness and that they are slightly early peaked with $t_{\text{rise}}/t_{\text{fall}} < 1.0$.

5. Linear Density Variation Region

Here we consider atmospheric density variations of the form $\rho(h) = \rho_0 (1 - h/h_0) H(1 - h/h_0)$, where ρ_0 is a constant, h_0 is a reference height and $H(1 - h/h_0)$ is the Heaviside step function. The linear density model approximates that of

an isentropic monatomic ideal gas atmosphere. Now, provided $x \leq 1$, so $I(h) = I_{\max} (1 - x)[1 - (G_L/2)(1 - 2x + x^2)]^2$, where the constant $G_L = U \rho_0 h_0/\mu_0 \geq 2$. By differentiating the equation for the intensity we find the height of maximum brightness to be $h_{\max}/h_0 = 1 - 2/\sqrt{10 G_L}$, and the end height is further determined as $h_E/h_0 = 1 - \sqrt{2/G_L}$, from which we derive $t_{\text{rise}}/t_{\text{fall}} = 1/(\sqrt{5} - 1) \approx 0.81$. Hence, we observe that the light curve must be slightly early peaked. A series of example profiles are shown in Figure 1c, where it can be seen that the light curves under the linear density approximation are nearly symmetrical. The basic shape of a light curve is often described according to the so-called F -value, where we take $F = (h_0 - h_{\max}) / (h_0 - h_E)$. A perfectly symmetric light curve will have an F -value of 0.5. For the light curves in Figure 1c we find that $F = 1/\sqrt{5} \approx 0.45$ indicating that they are, in fact, early peaked.

6. Discussion

Beech and Murray (2003) have previously suggested that the variations in observed Leonid meteor light curve morphology can be explained via a synthesis approach. Such synthesized light curves are constructed according to an aggregated dustball model in which a meteoroid is envisioned as being composed of numerous fundamental grains of varying mass (Hawkes and Jones, 1975). One of the reasons for adopting the synthesis approach was to explain the presence of near symmetrical and early peaked Leonid meteor light curves. Here we have shown that such light curves may also be generated via a classical approach provided that the atmospheric density in the region where ablation takes place varies in a linear, rather than an exponential, fashion. Of course, the Earth's atmospheric density in the region of meteoroid ablation does not 'naturally' vary in a linear fashion. This being said, it may just be possible that some of the faint, yet symmetric Leonid meteor light curves that have been observed are produced via the ablation of very low mass, monolithic, non-fragmenting, classical meteoroids. In the situation envisioned it is the low initial mass and high initial velocity that dictates very rapid ablation over a short atmospheric path in which the density variation is to first order linear in atmospheric height.

The constant atmospheric density approximation might only be applicable under a very restricted range of circumstances. One such situation is that concerning flare production when numerous small grains are released by, for example, the catastrophic break-up of a meteoroid. In this situation, the ablation of the grains will proceed very rapidly and over a very short atmospheric path, with this being especially so if the grains are released into the atmosphere in a region below their nominal on-set of ablation height. We do note, however, that for very small mass grains, thermal re-radiation and

rapid deceleration are important factors, and consequently the naïve analysis presented above is not likely to apply directly. A near constant atmospheric density condition may also be envisioned to apply in the ablation of meteoroids with Earth-grazing incidence and Earth ‘orbiting’ trajectories. In this case, it is the lack of significant height penetration by the meteoroid into the Earth’s atmosphere that is important. The August 10, 1972 fireball (Jacchia, 1974) is an example of an Earth-grazing object that barely penetrated the atmosphere. Indeed, over the 573-km trail length between the initial satellite-borne instrumentation detection height (Rawcliffe et al., 1974) and perigee, the $10^5 - 10^6$ kg body experienced a vertical height variation amounting to just 17 km and the velocity changed by less than 3% (Ceplecha, 1979). Unfortunately, no light curve has ever been published for this particular object.

Acknowledgment

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A MODEL OF SINGLE AND FRAGMENTING METEOROID INTERACTION WITH ISOTHERMAL AND NON-ISOTHERMAL ATMOSPHERE

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Abstract. The basic equations of physical theory of meteors are considered without the assumption of atmospheric isothermality. Analytical solutions are found in the case of single and fragmenting meteoroids, the fragmentation process being modeled in terms of the statistical theory of strength (Weibull, 1939). The comparison against a classical solution is made for the single body model. The comparisons against the observations and gross-fragmentation model results are made for a fragmenting meteoroid. An example of parametric investigations based on the obtained solutions is provided.

Keywords: Analytical solutions, meteoroids, non-isothermal atmosphere

1. Introduction

The classical physical theory of meteors (PTM) (Bronshten, 1983) assumes the atmosphere to be isothermal. The assumption of atmospheric isothermality gives the air pressure p and density ρ as exponential functions of geometrical altitude z over the planet surface: $p = p_0 \exp(-z/H)$, $\rho = \rho_0 \exp(-z/H)$, where p_0 and ρ_0 are the atmospheric pressure and density at the sea level, H is the constant scale height. In fact, the value of H non-monotonously depends on the height.

The influence of the scale height on a meteoroid motion was originally mentioned in the work of Pecina and Ceplecha (1983), who dealt with the interpretation of meteor observations. They emphasized the importance of the appropriate choice of the atmospheric model for the interpretation of the meteor observations and for the solution of the reversed problem of meteoric physics for bolide generating bodies. However the models assuming isothermal atmosphere still can be met today (e.g., Ceplecha et al., 1993; Hills and Goda, 1993; Lyne et al., 1996; Foschini, 2001; ReVelle and Ceplecha, 2002).

The present work is devoted to the theoretical investigation of the atmospheric non-isothermality influence on the meteoroids dynamics and to the development of the fragmentation model. Analytical solutions are obtained and exploited.

2. Basic Equations and Solution for a Single Body

The classical PTM is based on the following meteoroid drag and ablation equations (Bronshten, 1983):

$$M\dot{V} = -\frac{1}{2}AC_D\rho V^2, \quad Q\dot{M} = -\frac{1}{2}AC_H\rho V^3, \quad (1)$$

where V , M , A , Q are the meteoroid velocity, mass, cross-section area and effective heat of ablation correspondingly, the drag C_D and heat transfer C_H coefficients are to be given.

As the curvature of the Earth's surface, the gravitational force and lift force are neglected in the PTM, the meteoroid trajectory is a straight line having a given and constant inclination angle θ to the horizon. Then

$$\dot{z} = -V \sin \theta. \quad (2)$$

It is worth mentioning that this assumption is not valid for the meteoroids with shallow trajectories ($\theta < 10^\circ$).

The meteoroid cross section area is usually defined as $A = fM^{2/3} \delta^{-2/3}$, where f is the shape factor and δ is the density of the meteoroid in question. The last is assumed to be uniform. Traditionally f is set to be equal to 1.21, which corresponds to a spherical shape, as it does not strongly affect the ballistics. Its conservation means the assumption that the process of ablation does not change the initial meteoroid shape.

We proceed to a non-dimensional air pressure $\bar{p} = pp'^{-1}$ as a new argument, where p is the dimensional pressure and p' is the combination of constants with the dimension of pressure $p' = M_i g \sin \theta C_D^{-1} A_i^{-1}$, g is the acceleration due to the gravity. Keeping the ablation parameter $\sigma = C_H Q^{-1} C_D^{-1}$ constant we obtain the analytical solution to Equations (1) and (2):

$$M = M_i \exp(3(u - u_i)), \quad (3)$$

$$\bar{p} - \bar{p}_i = e^{-u_i} \Delta Ei(u_i, u), \quad (4)$$

where the subscript i stands for the initial values of variables, variable $u \equiv 6^{-1} \sigma V^2$ is introduced for short, $\Delta Ei(u_i, u) = Ei(u_i) - Ei(u)$, $Ei(x)$ is the

exponential integral function. The detailed derivation and analytical analysis of the solution (3–4) can be found in (Khanukaeva and Tirskey, 2005).

Expressions (3) and (4) are the dependences of body mass and velocity on the variable $\bar{p} = \bar{p}(z)$ which, in turn, depends on height. For the isothermal atmosphere this dependence is explicit and gives a direct connection between the meteoroid position and its velocity. This solution has been particularly investigated in the classical PTM (Bronshten, 1983).

A set of calculations was made for the comparison of solution (3–4) with that known in the classical PTM for a single body. Figure 1 represents the particles positions calculated as functions of time using the solutions obtained for the isothermal and non-isothermal atmospheres. The following entrance parameters were taken: $V_e = 18 \text{ km s}^{-1}$, $\sin\theta = 0.5$, $\delta = 2000 \text{ kg m}^{-3}$, $C_D = 1$ and sizes were varied from 10^{-4} to 0.1 m . We can see that the discrepancies in the meteoroid positions on the trajectory are of the order of several kilometers. This substantially exceeds the accuracy of the modern observational methods. The present solution can be applied to the observations interpretations using the Standard Atmosphere Tables to establish the correspondence between the air pressure and altitude. Extra numerical calculations are not necessary. Moreover, the analytical formulas for the velocity and mass of the body can be used for the purpose of numerical code verification.

In general, solution (3–4) has a universal form, depending on the only non-dimensional parameter u_i , valid for any non-fragmenting bodies in the non-isothermal atmosphere. It is applicable to the analytical studies of such parameters as the meteoroid deceleration, aerodynamic pressure, rates of mass and kinetic energy loss and others. Their investigation leads to deeper understanding of the process of meteoroids entries in the atmospheres of planets.

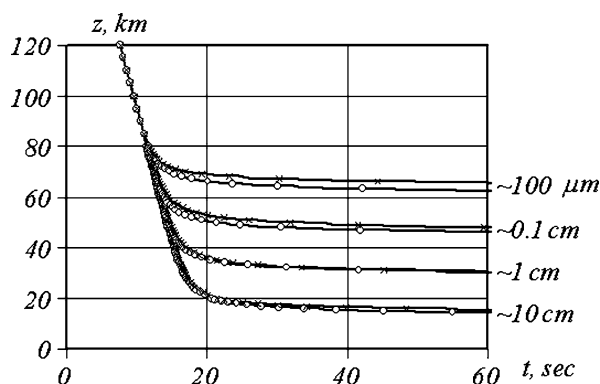


Figure 1. Positions of meteoroids of various sizes, defined in the frames of isothermal and non-isothermal models (o – isothermal; x – non-isothermal).

3. A Solution for Fragmenting Body

We assume the start of mechanical fragmentation process at the moment when the magnitude of the aerodynamic pressure ρV^2 becomes of the order of the body strength σ_* which, in turn, depends on its size, according to the statistical theory of strength (Weibull, 1939): $\sigma_* = \sigma_i (M_i / M_*)^\alpha$. Here σ_i is the strength limit of the initial body, α is scale parameter characterizing the homogeneity of the meteoroid material (the more homogeneous a material the less α), the subscript $*$ here and below corresponds to the values of the variables at the moment of the fragmentation beginning. The originating fragments may undergo further fragmentation if the aerodynamic load reaches their strength limit $\rho V^2 = \sigma_i (M_i / M_f)^\alpha$, where M_f is the fragment mass. All the fragments are accepted to be identical, so that $M_f = M/N$, where N is the total number of fragments. Using relation $\sigma_* \sim \rho_* V_*^2$, this quantity may be expressed as follows:

$$N = \frac{M}{M_*} \left(\frac{\rho V^2}{\rho_* V_*^2} \right)^{1/\alpha} = \tilde{M} (\tilde{\rho} \tilde{V}^2)^{1/\alpha}. \quad (5)$$

Here and below, the wave sign denotes the ratio of variables to their values at the moment of fragmentation beginning.

The fragments have finite velocities in the transverse direction. Individual bow shocks are formed shortly after the condition for the fragmentation is satisfied. This effect can be interpreted as the shift in heights, between the point of the realization of the fragmentation condition and the point where the fragments moving independently appear. The estimations of these shifts fulfilled in (Khanukaeva, 2002) give the values of about 1–3 km. In the present work we neglect this correction and treat all the fragments as moving independently after each act of fragmentation, though a more accurate consideration should include the stage of not-separated fragments motion with the common bow shock.

The drag and ablation equations for the total mass have the same forms as Equation (1) with the cross section area A proportional to $N^{1/3}$, where N is defined by Equation (5). The integral of the total mass has the same form as Equation (3). Using relation (2) and the definition of the variable scale height h in the form $h = -\rho(d\rho/dz)^{-1}$ (Martin, 1967), we proceed to $\tilde{\rho}$ as the independent variable. Having substitute M from Equation (3) and N from Equation (5) into the drag equation we obtain after the integration:

$$V = V_* \left(1 + \frac{\rho_* h_* C_D A_*}{3\alpha M_* \sin \theta} I(\tilde{\rho}) \right)^{-3\alpha/2}, \quad I(\tilde{\rho}) = \int_1^{\tilde{\rho}} \tilde{h} \tilde{\rho}^{1/3\alpha} d\tilde{\rho}. \quad (6)$$

In the case of $h = \text{const}$ the integral I ($\tilde{\rho}$) can be found explicitly and the solution (6) takes the following form

$$V = V_* \left(1 + \frac{\rho_* h C_D A_*}{(3\alpha + 1) M_* \sin \theta} \left(\tilde{\rho}^{\frac{1}{3\alpha} + 1} - 1 \right) \right)^{-3\alpha/2} : \quad (7)$$

In fact, solution (7) corresponds to the isothermal atmosphere, so the velocity of fragments can be expressed as an explicit function of their positions.

The importance of solutions (3) and (7) for the PTM is because of simplicity, which makes it very convenient for the study of fragments dynamics and application to the interpretation of observational data. The given solution allows us to find all characteristics of the meteoroid fragments at any moment. The number of fragments, the sizes of fragments, their velocity and position can be expressed as finite analytical functions of the air density (or the height over the planet surface).

Figure 2 represents the curves of the velocity and mass changes with the height for the entrance parameters of Lost City meteorite (Ceplecha, 1996): $V_i = 14.15 \text{ km s}^{-1}$, $M_i = 165 \text{ kg}$, $\delta = 3730 \text{ kg m}^{-3}$, $\theta = 38.32^\circ$, the initial strength corresponds to the altitude of the fragmentation start $z_* \approx 41 \text{ km}$, $\alpha = 0.4$ corresponds to the analysis of the amount of the fragments registered. The curves calculated according to solutions (3) and (7) are compared against the observational data and calculations made in the framework of the gross-fragmentation model (Ceplecha et al., 1993). One can see quite good correlation. It is worth emphasizing here that the gross-fragmentation model uses the known beforehand observational parameters of meteoroid at each point of fragmentation; it can be applied only after a meteoroid flight, while the present model and solution has a predictive character. The scenario of the fragmentation is automatically calculated. The visible difference of the curves for mass change at low altitudes is connected with the assumption of fragments identity. In reality they had very different sizes.

Solutions (3) and (7) are also rather convenient for various parametric investigations. For example, the analysis of the rate of meteoroid kinetic energy loss in the atmosphere dK/dz ($K = MV^2/2$) is seemed to be important. Solutions (3) and (7) provide the analytical expression for $(dK/dz)_{\max}$. Its investigation demonstrates the scale parameter α to be diagnostic one. While initial strength defines the starting point of the fragmentation, the scale parameter governs the rate of the fragmentation and the number of fragments resulting. The dependences of $(dK/dz)_{\max}$ and final number of fragments N_{total} on α are presented in Figure 3. It is worth mentioning that the scale parameter may vary in a wide range. The zero limit indicates ideally homogeneous material of the body, which disintegrates in the quasi-liquid

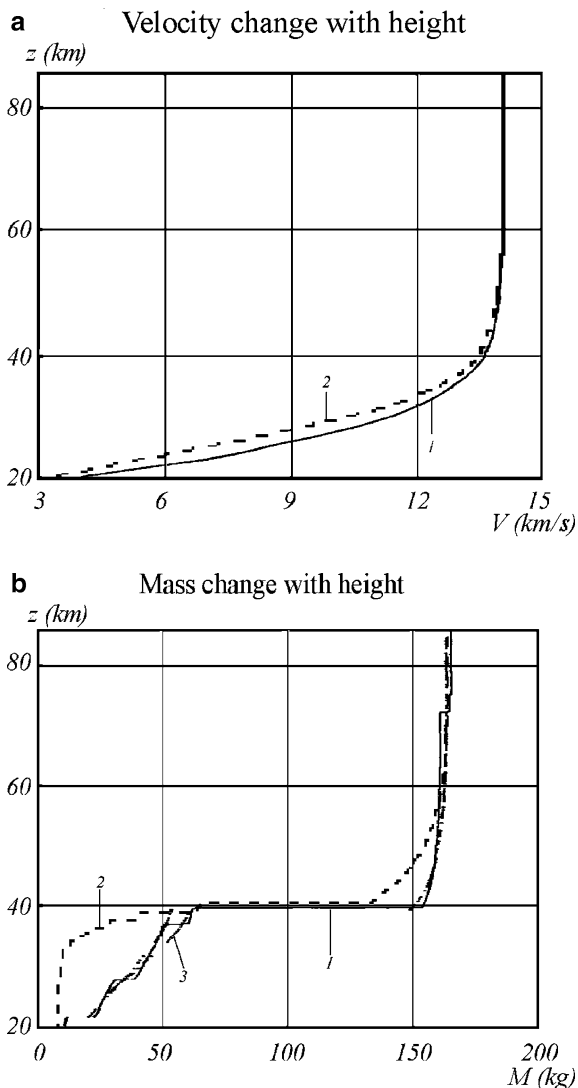


Figure 2. Velocity and total mass of Lost City meteoroid plotted as functions of height (1 – calculation of ReVelle and Ceplecha (2002); 2 – calculation of the present work; 3 – observations of Ceplecha (1996)).

mode. The pancake models are applied in this case. The infinite limit of α corresponds to a very strong body which does not fragment. Solutions (3) and (7) turn into the classical solution for a single body in this case. But, in fact, these limit conditions realize at rather moderate values of $\alpha \sim 2-5$. So, the narrow range of the scale parameter variation provides for the full range of homogeneity properties of the body. The case $\alpha = 1/6$ is shown

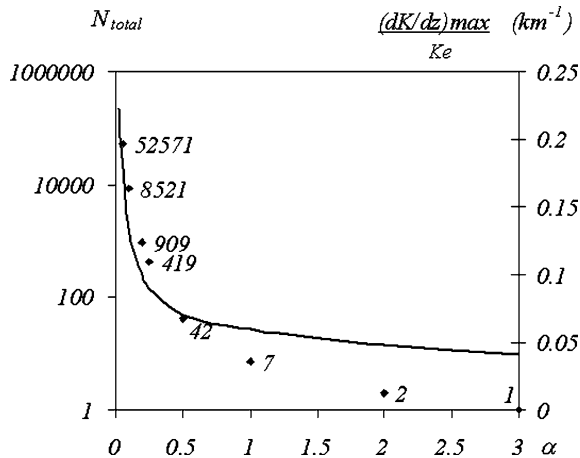


Figure 3. Maximal energy loss, divided by initial kinetic energy K_e (solid line) and final amount of fragments (bold dots with figures) as functions of the scale parameter.

(Khanukaeva, 2002) to be identical to the model assuming the successive doubling of the amount of the fragments. The intermediate value of $\alpha = 0.25$ used in the majority of papers on the PTM represents some average properties of the meteoroids material. But as it follows from Figure 3 even a slight variation of α results in dramatic change in the amount of fragments and energy deposited into the atmosphere. This demonstrates the importance of the accurate modeling of the meteoroids strength properties and scale parameter in particular. If α is known, the obtained solution answers the question of the amount of energy released in the atmosphere, and gives the point and the amount of maximal energy deposition.

4. Conclusion

In this paper the basic equations of the PTM (drag and ablation equations) for a single and fragmenting body are solved in analytical form without the assumption of the exponential decrease of air density with height. The velocity and mass of a single body were obtained as functions of a non-dimensional pressure and compared against the classical solution. These more precise solutions demonstrate noticeable discrepancy with classical ones and may be useful for the analysis and prediction of meteoroids ballistics and interpretation of observations.

The mechanical fragmentation of meteoroids was considered and an analytical solution for fragmenting body motion was obtained in a form which is especially simple in the case of the isothermal atmosphere. A number of comparisons with observations demonstrated rather good efficiency of the

model developed. The comparison with the Lost City meteorite data was given as an example. The solution obtained is convenient for various parametric investigations which can be fulfilled without any numerical computations. The study of the importance of the scale parameter α in the fragmentation model is a demonstration of such an investigation. A slight variation of the parameter α leads to a cardinal change in the scenario of meteoroid interaction with the atmosphere. This is the reason for more detailed future discussion and modeling of this parameter which in fact is not constant.

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SPUTTERING AND HIGH ALTITUDE METEORS

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Abstract. Conventional ablation theory assumes that a meteoroid undergoes intensive heating during atmospheric flight and surface atoms are liberated through thermal processes. Our research has indicated that physical sputtering could play a significant role in meteoroid mass loss. Using a 4th order Runge-Kutta numerical integration technique, we tabulated the mass loss due to the two ablation mechanisms and computed the fraction of total mass lost due to sputtering. We modeled cometary structure meteoroids with masses ranging from 10^{-13} to 10^{-3} kg and velocities ranging from 11.2 to 71 km s⁻¹. Our results indicate that a significant fraction of the mass loss for small, fast meteors is due to sputtering, particularly in the early portion of the light curve. In the past 6 years evidence has emerged for meteor luminosity at heights greater than can be explained by conventional ablation theory. We have applied our sputtering model and find excellent agreement with these observations, and therefore suggest that sputtered material accounts for the new type of radiation found at great heights.

Keywords: Ablation, high altitude, Leonid, light curve, meteor, sputtering

1. Introduction

The Leonid returns in the late 1990s produced observational evidence for several new meteor phenomena. Fujiwara et al. (1998) observed two meteors at heights above 160 km, higher than could readily be explained by conventional thermal ablation theory. LeBlanc et al. (2000) observed jet-like features and diffuse radiation transverse to the meteor trail in several Leonid meteors. Shortly thereafter Spurny et al. (2000a, b) reported on both a new type of diffuse luminosity as well as high altitude meteors. In this paper we will outline a model for meteor ablation which includes both thermal ablation and atomic physical sputtering ablation mechanisms. The model will then be applied to the observations of high altitude meteors and we will show that sputtering can explain the early low luminosity portion of the light curve for bright fast meteors.

2. Computational Model

A single body, isothermal, meteoroid in the free molecular flow regime is assumed. The differential equations of the thermal ablation model will not be given here, since they are covered in detail in Hill et al. (2005) and outlined briefly in Rogers et al. (2005a, b). We largely followed the approach developed by Adolfsson et al. (1996) for thermal ablation. The thermal ablation component of the model yields a very tiny amount of mass loss until the temperature approaches the meteoroid boiling point where rapid evaporation and light production occurs. While fragmentation is possibly significant for these meteors (Hawkes and Jones, 1975; Fisher et al., 2000; Hawkes et al., 2005), and it would alter the fine details of the model predictions, it would not change the main findings.

Physical sputtering in meteoroids is the process whereby atmospheric constituents incident on a meteoroid collide with surface atoms, thereby dislodging them from the material through a transfer of energy. Some of these liberated surface atoms escape immediately while others undergo collisions with other meteoroid atoms. This chain reaction of collisions causes enormous numbers of atoms to be sputtered away every second. While sputtering has been suggested as a meteor ablation mechanism at least as long ago as Öpik (1958) and it was included in Lebedinets et al. (1973) as part of an ablation model to mainly predict ionization curves, it has only very recently been considered in a detailed way as a mass loss mechanism.

The following two equations control the amount of sputtering expected during the ablation process. Equation (1) is the rate of change of meteoroid mass due to sputtering, where the summation index i refers to the i th atmospheric constituent.

$$\left(\frac{dm}{dt}\right)_{\text{sp}} = -2M_2Av\left(\frac{m}{\rho_m}\right)^{2/3} \sum_i n_i Y_i \quad (1)$$

The sputtering yield, $Y(E, \theta)$, is defined as the mean number of sputtered particles per incident atmospheric constituent. Equation (2) is a comprehensive relation which gives the sputtering yield at normal incidence as a function of energy.

$$Y(E, \theta = 0) = \frac{3.56}{U_0} \frac{M_1}{M_1 + M_2} \frac{Z_1 Z_2}{\sqrt{Z_1^{2/3} + Z_2^{2/3}}} \alpha \frac{R_p}{R} s_n(\gamma) \left[1 - \left(\frac{E_{\text{th}}}{E} \right)^{2/3} \right] \times \left(1 - \frac{E_{\text{th}}}{E} \right)^2 \quad (2)$$

The variables in Equations (1) and (2) are defined in Table I. For more detailed information regarding the sputtering model, see Rogers et al. (2005a, b). Our sputtering model has been guided by the approach to sputtering of astrophysical materials developed by Tielens et al. (1994).

If one considers the atmospheric ablation of a Leonid meteoroid (cometary structure, $v = 71 \text{ km s}^{-1}$), the sputtering yield ranges from 0.0001 to 0.83. The difference in sputtering yield occurs because of the various atmospheric constituents which interact with the meteoroid; the light hydrogen atoms have the almost insignificant sputtering yield of 0.0001 while the heavy argon atoms induce the most sputtering with the sputtering yield of 0.83.

Threshold energies for sputtering of a Leonid meteoroid range from 19.7 eV (hydrogen) to 47.8 eV (argon) and at the point of peak light intensity, the meteoroid is sputtering around 10^{25} atoms per second Table II.

Note that the composition of the meteoroid is significant in determining the sputtering yield; both the mean molecular mass per sputtered particle (M_2) and the bulk density (ρ_m) of the meteoroid are included in Equations (1) and (2). We used a mean value of 12 u for M_2 and a meteoroid bulk density value of 1000 kg m^{-3} in this research.

Meteoroid masses ranging from 10^{-13} to 10^{-3} kg in increments of 10, and initial meteoroid velocities from 11 to 71 km s^{-1} , were considered. A fourth

TABLE I
Sputtering parameters for Equations (1) and (2)

Symbol	Definition
M_2	Mean molecular mass per sputtered particle
A	Meteoroid shape factor
v	Meteoroid velocity
m	Meteoroid mass
ρ_m	Meteoroid density
n	Atmospheric number density
Y	Sputtering yield
U_0	Surface binding energy
M_1	Mass of incident atmospheric constituent
Z_1	Atomic number of incident atmospheric constituent
Z_2	Atomic number of meteoroid atoms
α	Dimension function of the mass ratio
$\frac{R_p}{R}$	Mean projected range to mean penetrated path length
$s_n(\gamma)$	Universal function
γ	Reduced energy
E_{th}	Threshold energy
E	Energy of incident atmospheric constituent

TABLE II

Sputtering yields and threshold energies for a collision between an atmospheric constituent and a Leonid meteoroid if a mean molecular mass per sputtered particle of 12 u is assumed for meteoroid material

Atmospheric Constituent	Threshold Energy (eV)	Sputtering Yield
Ar	47.8	0.83
O ₂	44.4	0.68
N ₂	42.4	0.58
O	35.2	0.32
N	33.7	0.28
He	22.2	0.04
H	19.7	0.0001

order Runge-Kutta method with a semi-adaptive step size was employed to numerically solve the system of coupled differential equations describing meteoroid flight through the atmosphere subject to both thermal and sputtering ablation. Data from the NASA MSISE 90 model was employed to develop detailed height profiles of the overall atmospheric mass density, and the atmospheric number density of each molecular species.

The sputtering and thermal ablation model calculated the luminosity of the meteor during its flight through the atmosphere by using the conventional meteor luminosity equation;

$$I = -\frac{\tau_I}{2} \frac{dm}{dt} v^2 \quad (3)$$

The luminous efficiency factor, τ_I , represents the fraction of the meteoroid's kinetic energy which is converted into luminous energy in the visual range. The precise value of the luminous efficiency factor is not well known. It is clear that the value of τ_I is of great importance to a model predicting light curves, however, the key results of this paper do not depend strongly on the precise value of τ_I . The reason for this is because both the early and maximum luminosity values would be changed by approximately the same factor.

In this paper, our luminous efficiency model is based on the relationships of Jones and Halliday (2001) who used atomic collision theory to obtain estimates for the luminous efficiency. In their approach they assumed the following relationship.

$$\frac{\tau_I \mu v^2}{2} = \epsilon \zeta \quad (4)$$

Here μ is the atomic mass of the ablated constituent under consideration which is assumed to have a mean excitation energy ϵ . ζ is an excitation coefficient which is a sum of excitation probabilities over a number of collisions. In principle ζ can be calculated if the scattering cross sections are known. Jones and Halliday combined data for iron atom collisions with theoretical atomic collision assumptions to develop a velocity dependence for ζ . They made three main assumptions in their model. They assumed that the scattering is isotropic in the centre-of-mass reference frame (the random scattering approximation, RSA). They also assumed that the trajectories of atoms undergo no deviation on ionization or excitation. Finally, they assumed that charge transfer takes place but the loss of velocity during charge transfer may be neglected. For an in-depth analysis of our luminous efficiency model, see Hill et al. (2005).

3. Mass Loss Results

We show in Figure 1 a plot of the fraction of a meteor's mass loss which is due to sputtering as a function of pre-atmospheric velocity and mass. A cometary structure meteoroid of mass density 1000 kg m^{-3} is assumed. The fraction of mass lost due to sputtering increases with decreasing meteoroid mass and increases with velocity to moderate velocity values at which point it begins to slowly decline. Clearly for meteor speeds above 30 km s^{-1} it is important to include sputtering. A more detailed consideration of mass loss

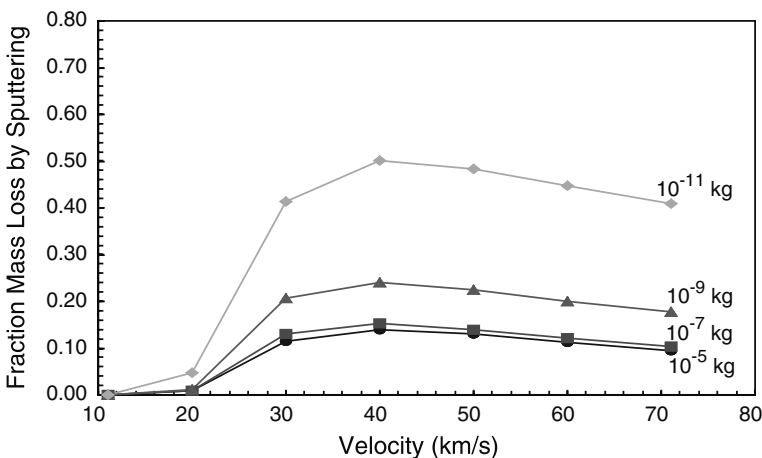


Figure 1. Plot of fraction of meteor mass loss which is due to sputtering versus the geocentric velocity (in km s^{-1}) for cometary structure meteoroids of different initial masses.

due to sputtering for a variety of types of meteoroid structure is given by Rogers et al. (2005a, b).

4. High Altitude Meteors

Fujiwara et al. (1998) and later Spurny et al. (2000a, b) observed luminosity from Leonid meteors at heights from 160 to 200 km. More recently, Koten et al. (2001) has found evidence for high altitude luminosity from non-Leonid meteors. It is difficult to explain such luminosity through thermal ablation since any substance which is sufficiently volatile to ablate at those heights would also be likely to have been sublimated during interplanetary flight. A major difference between thermal ablation and sputtering is that sputtering starts with the first atmospheric interaction and therefore can produce a small amount of ablation and potential luminosity at great heights. The expected light curves for a 0.006 kg cometary structure Leonid, if only thermal ablation and if both sputtering and thermal ablation are considered, are demonstrated in Figure 2. Brosch et al. (1996) proposed sputtering as a possible explanation for high altitude meteors, but no detailed quantitative comparisons with observations were made.

We investigated 17 high altitude Leonid meteors with published information (Fujiwara et al., 1998; Spurny et al., 2000a, b). The published data provided the zenith angle, the maximum light intensity, the beginning detection height, and the limiting magnitude of the detection system. We

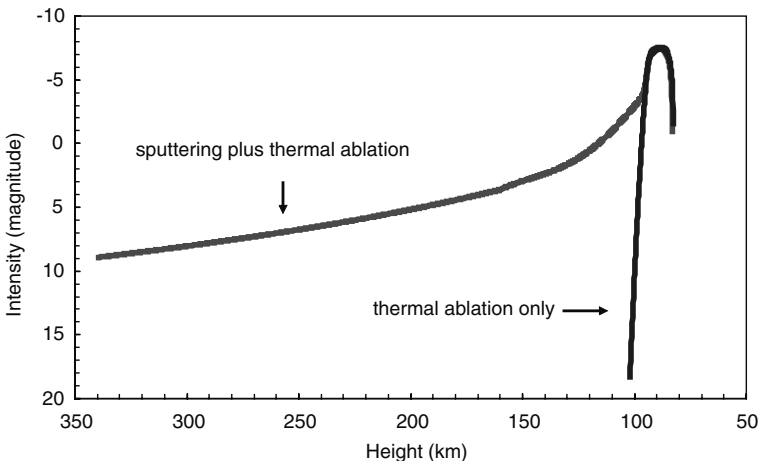


Figure 2. Light curve plot for a 0.006 kg cometary structure Leonid meteor when only thermal ablation is considered, and when both thermal and sputtering ablation are taken into account. The early, relatively low luminosity portion of the light curve provides a means of explaining luminosity at high altitudes for bright, fast meteors.

input the zenith angle (and velocity, 71 km s^{-1} for these Leonid meteors) into our model, and then varied the initial mass by small increments to find a mass value which produced the observed maximum light intensity. Once we had found a mass which matched the peak light intensity (within 0.1 astronomical magnitudes), we looked at the model output data at the height of first detection, and compared that light intensity to the system's limiting magnitude. Note that because these are Leonid meteors, we used a cometary structure with a meteoroid density of $\rho_m = 1000 \text{ kg m}^{-3}$. These data are presented in Table III.

TABLE III

Summary of sputtering and thermal ablation model results for observed high altitude Leonid meteors

Meteor	Observations					Model Results		
	$I_p(M)$	$z(^{\circ})$	$H_B(\text{km})$	$I_l(M)$	$m_{\infty}(\text{kg})$	$m_{\infty m}(\text{kg})$	$I_{pm}(M)$	$I_{Bm}(M)$
ln98002	-7.6	77.5	161	4	0.013	0.015	-7.50	3.09
ln98003	-8.5	75.8	168	4	0.051	0.03	-8.42	2.88
ln98008	-7.8	64.3	159	4	0.011	0.010	-7.86	3.27
ln98011	-7.5	60.6	183.6	6.5	0.01	0.006	-7.44	4.66
ln98012	-8.7	58.1	161	4	0.025	0.017	-8.68	3.00
ln98013	-7.1	55.6	154.9	6.5	—	0.004	-7.15	3.63
ln98015	-7.1	54.5	158	4	0.005	0.004	-7.18	3.85
ln98020	-7.6	45.5	160	4	0.006	0.005	-7.65	3.85
ln98023	-12.5	43.6	195	6.5	0.3	0.4	-12.50	2.04
ln98035	(-6.5)	28.8	156.7	6.5	—	0.0014	-6.49	4.52
ln98036	(-6.5)	26.0	161.5	6.5	—	0.0014	-6.52	4.83
ln98041	-13.2	23.2	191	4	1.1	0.6	-13.20	1.61
ln98043	-6.8	22.2	178.2	6.5	0.003	0.0017	-6.77	5.37
ln98044	-14.4	22.4	199	4	1.0	1.8	-14.40	1.10
ln98045	-5.7	20.8	146	4	0.001	0.00065	-5.72	4.42
Leonid1	-7*	45	160.7	7.0	—	0.003	-7.09	4.25
Leonid2	-4*	52	160.5	6.5	—	0.00025	-4.16	6.04

The observational data for the first 15 meteors was taken from Spurny et al. (2000a, b), while the data for the final 2 meteors was taken from Fujiwara et al. (1998). The observational data consists of I_p , the peak luminosity of the detected meteor expressed in astronomical magnitudes; z , the zenith angle of the meteoroid; H_B , the height at which the meteor was first detected; I_l , the limiting sensitivity of the observing system used expressed in astronomical magnitudes; m_{∞} , the initial photometric mass which was calculated from observations using the luminous efficiency data from Ceplecha and McCrosky (1976); $m_{\infty m}$, the meteoroid mass found to produce a maximum light intensity I_{pm} in the ablation model simulation comparable to that detected observationally; I_{Bm} , the luminous intensity of the meteor, in astronomical magnitudes, at the height of first observation according to the simulation. An asterisk denotes apparent observed magnitude and parentheses indicate that the values are only estimates.

As can be seen, there is very good agreement between the luminosity of the model meteor at the height where it was first observed and the limiting magnitude of the system. In each case the predicted luminosity is slightly brighter than the limit of the observing system, although it should be kept in mind that the model luminosity is expressed in terms of absolute meteor magnitudes while the observational limit is expressed in terms of apparent stellar magnitude. A check of the detailed output from our code indicated that significant thermal ablation had not begun at these high altitudes for any of the meteors (for the thermal parameters assumed). Our model suggests that at these heights light production is almost solely due to sputtering.

5. Discussion

We will first outline several potential limitations of the model employed here. The slight temperature dependence of the sputtering yield was not taken into account. The small deceleration due to particles sputtered from the front of the meteoroid was not considered (Coulson, 2002). We have assumed that the meteoroid has an isothermal temperature distribution, which should be a valid assumption for the range of meteor masses under consideration. We have assumed that the meteoroid collides with atmospheric molecules in the regime of free molecular flow. While the recent work of Campbell-Brown and Koschny (2004) has shown that there is a significant transition region, nevertheless free molecular flow is probably a valid first order approximation. We have not taken into account differential chemical ablation or possible fragmentation, but that should not strongly affect the overall results obtained. We have assumed that the same luminous efficiency relationships apply to sputtered and thermally ablated meteoric atoms.

Our model shows that sputtering is an important mechanism in meteor ablation, especially for light, low density, and moderate to high velocity meteoroids. A complete analysis of the importance of sputtering in meteoroid ablation is given in Rogers et al. (2005a, b). In the current work, we have in addition shown that sputtering appears to explain light production at high altitude in Leonid meteors. It is important to stress that these high altitude meteors cannot be explained by thermal ablation alone (except possibly if one evokes very volatile components and short interplanetary lifetimes after release from the parent comet). All of the observed meteors in Table III had not yet reached their intensive vaporization temperatures at the heights of observed luminosity if standard meteor thermal parameters are used.

An obvious extension of this work is to search for sputtering as a long, low luminosity early portion on the light curves of high altitude meteors. The optimum strategy would be to point a large aperture telescopic image intensified detection system (see e.g. Hawkes et al., 2005; Kaiser et al., 2005)

near the radiant of a meteor shower so that trails will be relatively short. This would allow one to detect with high sensitivity the early portions of meteor light curves. A coaxial larger field system could further increase the chance of detection of the maximum luminosity point. A question for future consideration is whether sputtering can explain the diffuse and jet-like features found on some high velocity shower meteors (LeBlanc et al., 2000, Spurny et al., 2000a, b).

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APPLICATION OF AN EQUILIBRIUM VAPORIZATION MODEL TO THE ABLATION OF CHONDRITIC AND ACHONDRITIC METEOROIDS

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Abstract. We modeled equilibrium vaporization of chondritic and achondritic materials using the MAGMA code. We calculated both instantaneous and integrated element abundances of Na, Mg, Ca, Al, Fe, Si, Ti, and K in chondritic and achondritic meteors. Our results are qualitatively consistent with observations of meteor spectra.

1. Introduction

Identification of meteoroid compositions is hampered because most meteoroids do not reach the Earth's surface. We must therefore rely on observations of meteors, i.e., the hot gas ablated from a meteoroid, to tell us about the composition of meteoroids. However the composition of the meteor may not reflect the bulk composition of the meteoroid because of incomplete ablation. In this paper, we attempt to bridge the gap between the observed meteor spectra and the initial unobserved meteoroid composition by examining the vaporization chemistry of meteoroids.

Meteoroid ablation models usually focus on physical properties (initial mass, density, porosity) and motion (velocity, fragmentation) but do not consider the variable compositions of meteoroids (Pecina and Ceplecha, 1983; Ceplecha et al., 1993; Campbell-Brown and Koschny, 2004; Zinn et al., 2004). Instead a total vapor pressure is assumed for a generic “stony” object. Other models assume complete evaporation of CI chondritic material (Popova et al., 2000). However, observations show that meteors rarely have chondritic abundances of elements such as Ca, Al, and Ti (Ceplecha et al., 1998). Many meteor spectra are also time-variable, e.g., the abundance of Na in a meteor's spectra often decreases as the meteor descends through the Earth's atmosphere (Borovička et al., 1999).

McNeil et al. (1998) used the MAGMA code and developed a differential ablation model in which metals ablate sequentially along a meteor's trajectory based upon volatility. Their results help explain lidar observations of single- and double-element meteor trails of Na, K, Ca, Ca^+ , and Fe, specifically the preponderance of single-element trails and the deviation of element ratios from CI chondritic values in the double-element trails (Von Zahn et al., 2002; Murad and Roth, 2004).

In this paper, we use the MAGMA code to model fractional vaporization of chondritic and achondritic meteoroids. Our goal is to constrain the initial composition of meteoroids based upon observed elemental abundances in their meteor spectra. We explicitly assume that the vaporizing material does not interact with the atmosphere and that there are no kinetic deviations from equilibrium. We will model interaction with the atmosphere in later work. We also assume chemical equilibrium between the meteoroid and its evolved vapor. In later sections, we justify our assumptions and compare our results to observed meteor spectra. Our results complement those of McNeil and colleagues but do not duplicate their work.

2. Methods

The MAGMA code is a mass balance, mass action code that computes fractional vaporization from a silicate melt composed of the oxides SiO_2 , MgO , FeO , Al_2O_3 , CaO , TiO_2 , Na_2O , and K_2O . The MAGMA code uses the ideal mixing of complex components model developed in the 1980s by Hastie and colleagues at the U.S. National Bureau of Standards to simultaneously solve for the composition of the silicate melt, melt–vapor chemical equilibria, and vapor phase chemical equilibria. The code's operation, thermodynamic database, and validation against experimental studies are described in our prior papers and references cited therein (Fegley and Cameron, 1987; Schaefer and Fegley, 2004).

The MAGMA code calculates bulk element ratios in the vapor at individual points and integrated along a vaporization pathway, and gas speciation. We focus on the bulk element ratios in the vapor, both step-wise and integrated. Bulk element ratios refer to the ratio of the sums of the mole fractions for gas species of two elements; e.g., Mg/Fe refers to $\Sigma(X_{\text{Mg}} + X_{\text{MgO}}) / \Sigma(X_{\text{Fe}} + X_{\text{FeO}})$. Future work will describe gas speciation. The results are graphed as a function of the mass fraction of the melt that has been vaporized (F_{vap}). This quantity can be qualitatively identified with a decrease in altitude since a meteoroid loses mass as it descends through the atmosphere. A quantitative relationship between F_{vap} and altitude, which depends upon such variables as meteoroid mass, meteor velocity, beginning height, etc., has previously been computed by Murad and colleagues (McNeil et al.,

1998; Murad and Roth, 2004). Such calculations are beyond the scope of this paper, so our comparisons to meteor spectra will necessarily be of a qualitative nature.

The calculations shown here are for $T = 1500\text{--}6000$ K. All calculations are isothermal. We chose this temperature range based upon meteor observations. Ablation typically begins at temperatures of about 1500–2500 K (Ceplecha et al., 1998), and meteor spectra typically have temperatures in the range 4000–5000 K (Borovička, 1993, 1994). Our temperature range spans these temperatures. Extreme high temperatures (>4000 K) are shown for trends.

Meteoroids presumably have compositions similar to meteorites. The majority of meteorites ($>70\%$) are chondrites, which are subdivided into ordinary, carbonaceous, and enstatite chondrites. All chondrites give very similar results; here, we show results for CI chondrites, which have solar abundances of the major non-volatile elements (Lodders, 2003). Results for achondrites (eucrites, diogenites, aubrites) are more diverse. We show results for eucrites, which are the most abundant type of achondrite ($\sim 33\%$ of all achondrites). We used the composition of the Juvinas eucrite, from Kitts and Lodders (1998). For both compositions, all iron is given as FeO (s), and the compositions have been normalized to 100% on a volatile-free basis. Differences in results for chondrites and achondrites are discussed below.

3. Results

Figures 1 and 2 show the bulk atomic ratios of Na, Mg, Ca, and Al relative to Fe integrated along the vaporization pathway above a CI chondritic meteoroid and a eucritic meteoroid, respectively. Figure 3 shows the bulk atomic ratios of Na and Ca relative to Fe at individual points along the vaporization pathway above a CI chondritic meteoroid. We chose Fe as the normalizing element because abundances determined from meteor spectra are typically given relative to Fe (e.g., Borovička, 1993). We will discuss differences in results based upon the choice of element used for normalization. Below, we discuss the results for each element separately.

3.1. SODIUM

In Figures 1a and 2a the initial integrated atomic Na/Fe ratios at very low F_{vap} are much larger than the solar value, especially at lower temperatures. As temperature increases, the initial Na/Fe ratio decreases to the solar value. For the CI chondrite, the Na/Fe ratio reaches solar values at ~ 40 wt% vaporized when $T = 1500$ K; however, at 6000 K, the Na/Fe ratio

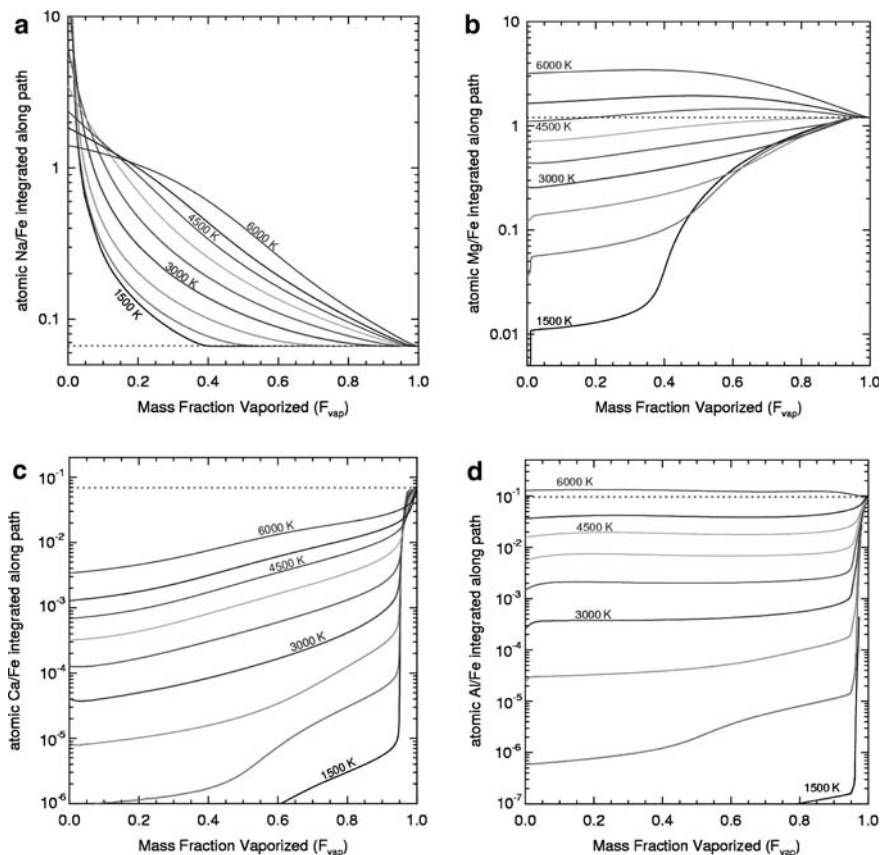


Figure 1. Integrated element abundances relative to Fe in the vapor over a CI chondritic melt, at various temperatures. Each line represents an isothermal vaporization path. In all figures the lines are spaced at 500 K intervals from 1500 K to 5000 K and the 6000 K isotherm is also shown. The dashed line marks the solar composition. (a) Na/Fe (b) Mg/Fe (c) Ca/Fe (d) Al/Fe.

does not reach the solar value until $\sim 100\%$ vaporization. For the eucrite, the atomic Na/Fe ratio drops below the solar value for $F_{\text{vap}} > 20\%$ at 1500 K and $> 90\%$ at 6000 K. These trends indicate that the volatility of Fe increases as temperature increases. The atomic Na/Fe ratio over the eucrite is closer to the solar value than the CI chondrite value for most conditions (T and F_{vap}).

The initial step-wise atomic Na/Fe ratios shown in Figure 3a are much larger than solar and rapidly decrease. The Na/Fe ratio drops more slowly as temperature increases for both chondritic and achondritic meteoroids. The curves for the atomic Na/Fe ratio above the eucrite (not shown) are much flatter than those of the CI chondrite, similar to the integrated ratios (Figure 2a).

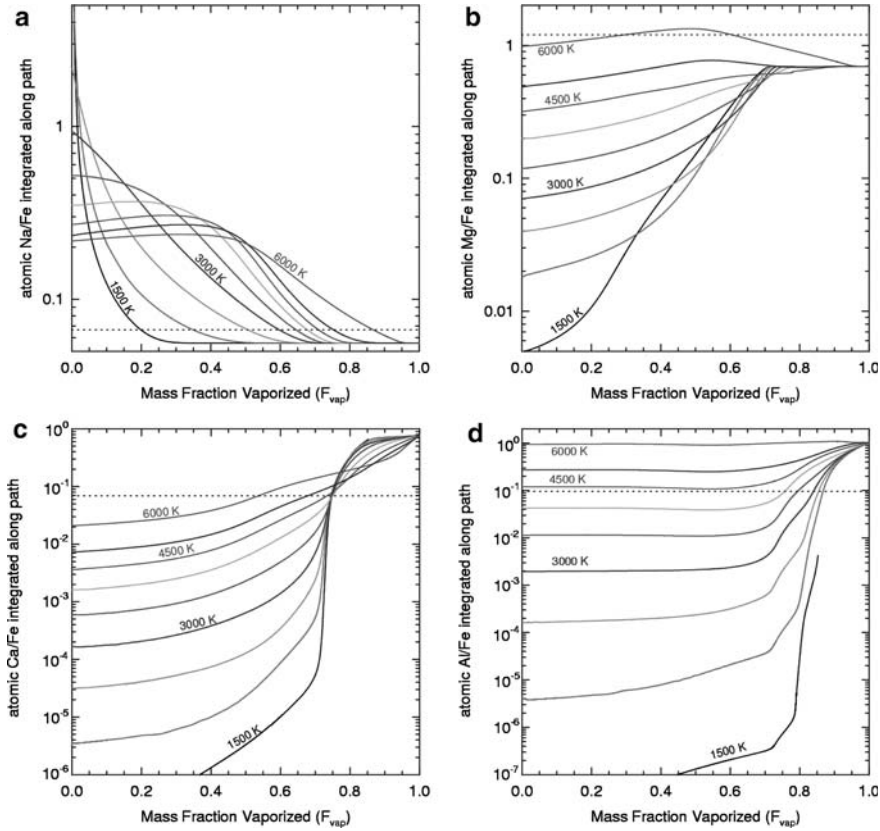


Figure 2. Integrated element abundances relative to Fe in the vapor over a eucritic melt, at various temperatures. (a) Na/Fe (b) Mg/Fe (c) Ca/Fe (d) Al/Fe.

Figure 4 shows the integrated atomic Na/Mg and Ca/Mg ratios over a CI chondrite. For a given F_{vap} , the integrated Na/Fe atomic ratio over a chondrite increases as temperature increases (Figure 1a), whereas the integrated Na/Mg atomic ratio decreases (Figure 4a). At a given temperature, the Na/Mg ratio approaches solar values at much higher F_{vap} compared to the Na/Fe ratio. The difference between ratios relative to Fe and Mg is most extreme for volatile elements (e.g., Na, K), and less important for refractory elements (e.g., Ca, Al). The integrated Ca/Mg atomic ratios (Figure 4b) increase slightly less rapidly than Ca/Fe as temperature increases.

3.2. MAGNESIUM

In Figures 1b and 2b the integrated atomic Mg/Fe ratio generally increases as temperature and F_{vap} increase. Magnesium is depleted over the eucrite

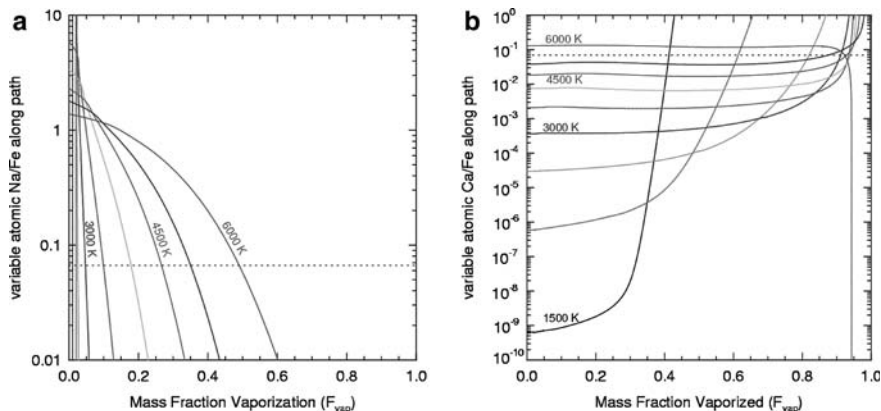


Figure 3. Instantaneous element abundances relative to Fe in the vapor over a CI chondritic melt, at various temperatures. (a) Na/Fe (b) Ca/Fe.

compared to the CI chondrite. The atomic Mg/Fe ratio over the CI chondrite is about solar for $T=4000\text{--}4500\text{ K}$. At $T>4500\text{ K}$, Mg/Fe is greater than solar values, and at $T<4000\text{ K}$, Mg/Fe is less than solar. The atomic Mg/Fe ratio over the eucrite is solar at $\sim 6000\text{ K}$. For $T<6000\text{ K}$, the Mg/Fe ratio over the eucrite is subsolar.

Though not shown, we also calculated the step-wise atomic Mg/Fe ratios for both the CI chondrite and the eucrite. Generally, the Mg/Fe ratio increases with F_{vap} because Mg is less volatile than Fe. At low temperatures, the Mg/Fe ratio starts out at $\sim 1\%$ of solar and quickly skyrockets to values greater than 1000 as all of the Fe is vaporized. As temperature increases, the curves begin to level out, similar to the Ca/Fe ratios shown in

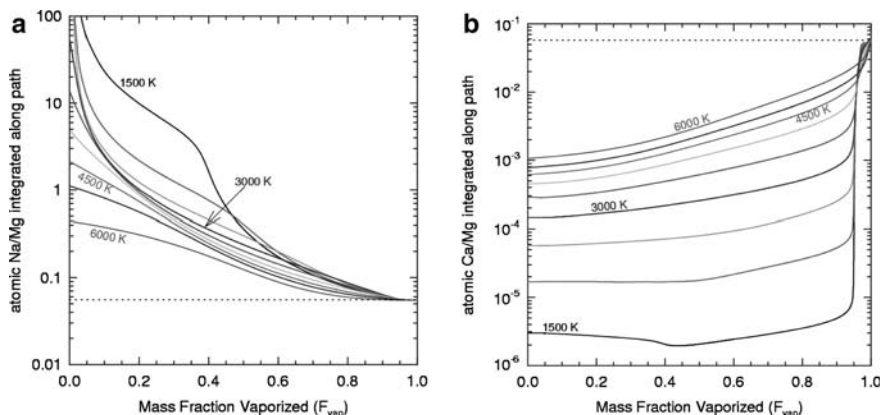


Figure 4. Integrated element abundances relative to Mg in the vapor over a CI chondritic melt, at various temperatures. (a) Na/Mg (b) Ca/Mg.

Figure 3b. Between 4000–4500 K, the Mg/Fe ratio over the CI chondrite is about solar for all $F_{\text{vap}} < 0.8$. The Mg/Fe ratio above the eucrite shows similar behavior but is shifted down because the eucrite is Mg-poor relative to the CI chondrite. The eucrite has solar Mg/Fe ratios at 6000 K for all $F_{\text{vap}} < 0.5$.

3.3. CALCIUM

In Figures 1c and 2c the integrated atomic Ca/Fe ratios increase with temperature and F_{vap} . The eucrite is a Ca-rich achondrite, with more Ca than the CI chondrite, so the Ca/Fe ratios above the eucrite are larger than those above the CI chondrite. The atomic Ca/Fe ratio over the chondrite approaches the solar value for $F_{\text{vap}} > 0.90$. The atomic Ca/Fe ratio over the eucrite is approximately solar at $T > 6000$ K and exceeds the solar value for all $F_{\text{vap}} > 0.70$.

In Figure 3b the initial step-wise atomic Ca/Fe ratios over a CI chondrite are much less than solar at low temperatures and increase with F_{vap} . The abrupt increase in the Ca/Fe ratio at low temperatures is due to the early loss of all Fe from the melt. At higher temperatures, the stepwise Ca/Fe ratio flattens, and is fairly constant for most F_{vap} . It has an approximately solar value between 5000 and 6000 K. Similar behavior is seen above a eucritic meteoroid, although the Ca/Fe ratio is significantly higher, due to the larger initial Ca content of the eucrite. The Ca/Fe ratio above the eucritic meteoroid is approximately solar between 4000 and 4500 K.

3.4. ALUMINUM

As Figures 1d and 2d show, there is essentially no Al in the vapor at low temperatures. The atomic Al/Fe ratio increases with temperature and F_{vap} . The eucrite is Al-rich compared to the CI chondrite. Therefore, the Al/Fe ratios above the eucrite are larger than those above the CI chondrite. The atomic Al/Fe ratio over the CI chondrite is approximately solar between 5000 and 6000 K. The atomic Al/Fe ratio over the eucrite is approximately solar between 4000 and 4500 K.

As with Mg and Ca, the step-wise atomic Al/Fe ratios begin at values much lower than solar and increase with temperature and F_{vap} . As temperature increases, the Al/Fe lines flatten, but they still increase slightly with F_{vap} unlike the Ca/Fe ratios in Figure 3b. The Al/Fe ratios over the CI chondrite only approach the solar value at $F_{\text{vap}} > 0.90$. At 6000 K, the Al/Fe ratio over the CI chondrite is 3–10% of the solar value for all $F_{\text{vap}} < 0.90$. The Al/Fe

ratio over the eucrite is slightly higher at all temperatures and is greater than the solar value for all $F_{\text{vap}} > 0.5$.

4. Discussion

4.1. EQUILIBRIUM VS. KINETICS

Modeling the ablation of a meteoroid has two extreme end members: (a) ablation controlled entirely by kinetics (e.g., sputtering, chemical kinetics) or (b) ablation controlled entirely by equilibrium chemistry (vaporization). Most ablation models are of the first type, focusing purely on kinetics. Our model assumes that equilibrium chemistry is all-important. True meteor ablation is certain to be a combination of both kinetic and equilibrium effects. However, in order to identify deviations from equilibrium, we must first study pure equilibrium. By knowing the equilibrium composition, we may be able to determine the extent to which chemical and physical kinetic effects cause deviations from equilibrium.

We looked at chemical lifetimes for the vaporized species to see if chemical equilibrium is attained within typical meteor flight times. For example:



has a chemical rate constant (Le Picard et al., 2001) of:

$$k_1 = 1.72 \times 10^{-10} (T/300 \text{ K})^{-0.53} \exp(-17/T) \text{ cm}^3 \text{ s}^{-1}. \quad (2)$$

Using our calculated O_2 partial pressure from vaporization, we calculate a chemical lifetime for Si (g) of ~ 0.008 s at 1500 K, $\sim 10^{-9}$ s at 4000 K, and $\sim 10^{-11}$ s at 6000 K. These lifetimes are much shorter than the typical flight time of a meteor (~ 0.1 – 0.5 s), so chemical equilibrium may occur in the gas surrounding the meteoroid. We also assume chemical equilibrium within the meteoroid itself, which is valid for meteoroids that are small enough to melt completely (0.05–0.5 mm radius, Ceplecha et al., 1998) because diffusion and heat conduction do not significantly effect vaporization. Most micrometeoroids $< 100 \mu\text{m}$ in diameter will not reach temperatures above ~ 2000 K, and they may only experience partial melting or no melting at all, so equilibrium vaporization may not be valid for them. Micrometeoroids between 100 and $1000 \mu\text{m}$ in diameter can reach temperatures up to ~ 3000 K, and many completely evaporate (Love and Brownlee, 1991). Centimeter and greater-sized meteoroids may reach higher temperatures due to compressional shock heating, but do not melt com-

pletely; in these meteoroids, melt layers are typically confined to “skins” a few millimeters thick (Ceplecha et al., 1998). Diffusion and heat conduction are important in these larger meteoroids; therefore, chemical equilibrium is a less valid assumption.

4.2. COMPARISON OF RESULTS TO OBSERVATIONS OF METEOR SPECTRA

Our model is generally consistent with observations of the elemental abundances in Leonid meteors (Borovička et al., 1999), in which Na peaks at the beginning of the meteor’s flight path and rapidly decreases, while Mg peaks later in the flight. Borovička et al. (1999) show the time-variable abundances of Na and Mg in a variety of other meteoroids in their Figure 6. Some of these meteors are consistent with our calculated curves for a CI chondrite, whereas others, such as one of the Taurids (SZ 28) and one of the sporadics (SZ 132), are more consistent with our calculated curves for a eucrite. This is primarily due to the high and relatively constant Na abundances in the meteors. As discussed above, the eucrite meteoroid has fairly constant Na/Fe ratios, which qualitatively agrees with the Na/Fe ratios observed in SZ 28 and SZ 132. The difference in the Na/Fe ratios between the CI chondrite and the eucrite is primarily due to the eucrite’s lower initial Na abundance. Therefore, we suggest that these meteors had an initial Na abundance less than that of our CI chondrite.

Trigo-Rodriguez et al., (2004) show time-variable elemental abundances for a Leonid meteor (LEO) in their Figure 4. Their spectra show that the Na/Si ratio is fairly constant over most of the meteor’s height for temperatures of 4400–5000 K, and then it decreases as temperatures reach 5800 K. According to our results, this is consistent with an initial meteoroid slightly depleted in Na relative to our CI chondrite. Trigo-Rodriguez et al. (2004) suggest that the meteors they studied are enriched in Na relative to solar; we suggest that this may not be true unless there is an accompanying enrichment in Si. Figure 4 of Trigo-Rodriguez et al. (2004) also shows the time-variable Mg/Si, Ca/Si, and Fe/Si ratios for the same meteor (LEO). Comparing these abundances to our results, we find that the meteoroid may have larger Mg, Ca and Fe abundances and/or a smaller Si abundance relative to our CI chondrite in order to get similar elemental ratios in the gas.

Some meteors show complex behavior not explained by our model. These spectra can often be explained if the initial spectra is due to ablation of a fusion crust (for larger meteors), and spikes in the element abundances are due to sudden fragmentation of the meteoroid and ablation of material that was previously protected from ablation by the fusion crust. For example, Borovička (1993) analyzed the spectrum of a fireball, which is a meteor of large magnitude associated with a large meteoroid. In Figure 14 of this paper,

Borovička gives the time-variable element to Fe ratios as a function of height. The abundances (e.g., Ca, Ti, Cr, Na) show several peaks, which indicate a sudden increase in vaporization and which are accompanied by an increase in the meteor's temperature. Our results cannot reproduce such a spike in the element abundances unless we overlay a separate vaporization path for a body of the original composition at a higher temperature, which vaporizes at a much faster rate. This is consistent with Borovička's conclusion that the flares correspond to fragmentation events.

A caveat about interpretation: Here we present bulk elemental abundances in the vaporized gas, i.e., the abundance of Na includes the species Na, Na₂, NaO, Na₂O, and Na⁺. Observations, however, typically only give abundances for the neutral (and possibly singly ionized) monatomic gases. The outcome is that the results presented in our figures may differ slightly from observed meteor abundances for a meteoroid of the same composition. The discrepancy depends strongly on the element and is most severe for Al, which occurs in the gas primarily as AlO (g). The gas speciation is computed by the MAGMA code and will be given elsewhere.

5. Summary

We applied results from the MAGMA code, an equilibrium vaporization model, to the problem of meteoroid ablation. In particular, we looked at the element ratios in the meteor. Hopefully, this data can be used to estimate the original meteoroid composition from meteor observations. In future work, we will compare the calculated melt compositions from MAGMA to analyzed compositions of micrometeorites. In principle, this will tell us if equilibrium is a valid assumption when studying meteoroid vaporization. We will also add additional compounds and elements of interest, such as H₂O, S, C, Mn, Co, Cr, Ni, etc., which are observed in meteor spectra, and other trace elements that are analyzed in micrometeorites. In this way, we may be able to make greater distinctions between types of meteoroids based upon meteor spectra. Additionally, we plan to model interaction of the vaporized gas with hot air (e.g., N₂, O₂, CO₂, etc.), which will be useful for studying meteor trains. The MAGMA code is freely available upon request.

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PREDICTING MARTIAN AND VENUSIAN METEOR SHOWER ACTIVITY

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Abstract. Based on the number of planet-approaching cometary orbits at Mars and Venus relative to the Earth, there should be ample opportunities for observing meteor activity at those two planets. The ratio of planet-approaching Jupiter family comets (JFCs) at Mars, Earth, and Venus is 4:2:1 indicating that JFC-related outbursts would be more frequent at Mars than the Earth. The relative numbers of planet-approaching Halley-type comets (HTCs) implies that the respective levels of annual meteor activity at those three planets are similar. We identify several instances where near-comet outbursts (Jenniskens, P.: 1995, *Astron. Astrophys.* **295**, 206–235) may occur. A possible double outburst of this type at Venus related to 45P/Honda-Mrkos-Padjusakova may be observable by the ESA *Venus Express* spacecraft in the summer of 2006. Similarly, the Japanese *Planet-C* Venus orbiter may observe an outburst related to 27P/Crommelin's perihelion passage in July 2011. Several additional opportunities exist to observe such outbursts at Mars from 2019 to 2026 associated with comets 38P/Stephan-Oterma, 13P/Olbers and 114P/Wiseman-Skiff.

Keywords: Mars, meteor outbursts, meteor showers, meteors, Venus

1. Introduction

Meteor astronomy employs the atmosphere of the Earth as a large area detector for 0.1 mm to decimeter-sized meteoroids. These are smaller than can be detected individually in space with Earth-based telescopes but of too low flux density to make their detection with conventional space-based dust detectors practical. Monitoring the atmospheres of other planets for meteor activity offers the opportunity to study the parent bodies of as yet undetected meteor showers as well as providing better statistics on the spatial distribution and dynamical evolution of such meteoroids in the solar system. It provides opportunities to test ablation models on atmospheres of different structure and composition than the Earth's. Finally, predicting enhancements of large meteoroid flux associated with planet-intercepting streams allows interplanetary spacecraft operators to mitigate the risk of impact and potential loss of mission.

Both Mars and Venus have atmospheres dense enough to ablate meteoroids as bright meteors. Adolfsson et al. (1996) have shown that fast ($>30 \text{ km s}^{-1}$) meteoroids would be of similar brightness in the atmospheres of Mars and the Earth while lower speed meteoroids would be fainter at Mars. Martian meteors would reach their maximum luminosity 10–20 km lower than at the Earth. A probable meteor trail was recently detected by the *Spirit* rover on Mars (Bell et al., 2004).

Christou (2004) has argued that, based on the venusian atmospheric structure, meteoroids would reach their maximum ablation rate, and thus their maximum meteor luminosity, between 100 and 120 km, above the cloud and haze layers that surround Venus (Esposito et al., 1983). They would also be intrinsically brighter, typically by one or two magnitudes, than at the Earth, rendering them readily detectable from orbiting spacecraft. Indeed, the UVS instrument onboard the *Pioneer Venus Orbiter* spacecraft detected a meteor-trail-like phenomenon in February 1979 (Huestis and Slinger, 1993).

2. Relative Abundance of Shower Parents

A small minimum orbit-to-orbit distance or MOOD (Christou and Beurle, 1999), hereafter denoted as Δ , offers a necessary, but not sufficient, criterion for a comet to produce an observable meteor shower in the atmosphere of the Earth. Indicators of this type have been used to identify possible meteor shower parent bodies at Venus (Beech, 1998; Christou, 2004; Selsis et al., 2004) and Mars (Christou and Beurle, 1999; Treiman and Treiman 2000; Larsen, 2001; Selsis et al., 2004). Such results, taken as a statistical population, may also be used to make statements on the relative abundance of meteor showers at the three planets. In a sample of 158 multi-apparition comets available within the JPL DASTCOM database, the respective number of comets approaching Mars, Earth and Venus to within 0.1 AU is 34, 15 and 9, mostly consisting of Jupiter family comets (JFCs – $P < 20 \text{ yr}$) but also including Halley-type comets (HTCs – $P > 20 \text{ yr}$) in all three cases (3, 3 and 5, respectively – Figure 1). Earth has two very-close-approaching ($\Delta < 0.01 \text{ AU}$) HTCs, namely 55P/Tempel-Tuttle and 109P/Swift-Tuttle, parents of the Leonid and Perseid meteor showers respectively. All three HTCs (including 1P/Halley in addition to the above) are parent bodies of prominent annual showers (η Aquarids/Orionids – 1P/, Perseids – 109P/) or intense outbursts (Leonids – 55P/) compared to only a quarter of the Earth-approaching JFCs (Ursids – 8P/Tuttle, Draconids – 21P/Giacobini-Zinner, π Puppids – 26P/Grigg-Skjellerup). The number of Mars-approaching JFCs is 31 compared to 12 at the Earth, three of which (9P/Tempel 1, 114P/Wiseman-Skiff, 146P/Shoemaker-LINEAR) approach to within 10^{-2} AU (Christou and Beurle, 1999; Selsis et al., 2004). Thus, JFC-associated meteor

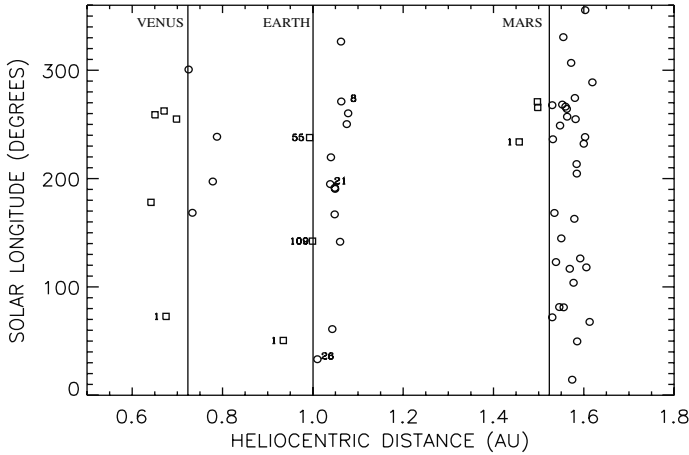


Figure 1. Cometary approach circumstances for Venus, Earth and Mars. Planetary orbits are depicted as vertical lines. Halley Type Comets (HTCs) are denoted as boxes at the left of each orbit while Jupiter Family Comets (JFCs) are shown as circles at the right. The apparent separation between a given comet and planetary orbit is the true minimum distance Δ between the keplerian orbits. Numbered comets correspond to known meteor shower associations at the Earth.

outbursts (also discussed in Section 3.2) may be a more common phenomenon on Mars than the Earth.

3. Individual Shower Predictions

Barring an all-out effort to fully characterise the venusian and martian meteor “years”, the first aspects to be observed and studied will likely be occasions of strong recurring (“annual”) or episodic (“outburst”) activity, for example a Perseid, Geminid or Quadrantid-strength shower in the first instance, and a Leonid- (HTC) or Draconid-type (JFC) outburst in the second. These studies would be carried out mainly from orbiting probes but Earth-based detection may be possible for fireball-rich streams (Beech and Brown, 1995; P. Jenniskens, private communication). Predictions on individual showers is, therefore, a topical issue and can be addressed initially through the Δ quantity.

3.1. ANNUAL SHOWERS

Strong annual activity is usually associated with Halley-type comets (Jenniskens, 1994). Their orbits are stable for several tens of orbital revolutions, allowing a complete stream to form. In Table I, we provide a list of HTC

TABLE I

Circumstances of Halley-type comet orbits approaching those of Mars, Venus and the Earth

Comet	Planet	v (km s ⁻¹)	Δ (AU)	$\lambda_{\odot}$ (degrees)
1P	M	54	0.0670	231
13P	M	27	0.0266	268
38P	M	13	0.0260	263
1P	E	67	0.0662	48
55P	E	72	0.0078	235
109P	E	60	0.0015	139
1P	V	80	0.0487	70
12P	V	53	0.0731	256
27P	V	28	0.0255	252
35P	V	46	0.0821	175
122P	V	59	0.0530	260

The quantity denoted as v is the atmospheric impact velocity at the planet while Δ is the minimum orbit-to-orbit distance and $\lambda_{\odot}$ is the solar longitude.

orbits that approach the orbits of Earth, Venus and Mars. The Δ cutoff is 0.1 AU. This is larger than the value used in Selsis et al. (2004). Also, unlike Christou and Beurle (1999) we do not impose an impact speed restriction. We see that comet 1P/Halley is the only triple-planet HTC approacher in the list raising interesting possibilities for comparative studies of its meteoroid stream. It approaches the venusian orbit slightly closer (0.05 AU) and slightly faster (80 km s⁻¹) than the Earth's. One would also expect related meteor activity at Mars, although the stream particle density there is expected to be lower than at the Earth due to it being further away from perihelion. Venus-approachers 12P/Pons-Brooks, 27P/Crommelin and 122P/de Vico form a cluster in solar longitude spanning 8° across which translates into up to three distinct meteor showers within a period of five Earth days. The most promising candidate for an annual meteor shower on Mars appears to be 13P/Olbers, combining a relatively high impact velocity (27 km s⁻¹) and a small value for Δ (0.03 AU).

3.2. METEOR OUTBURSTS

Intense meteor activity also manifests itself in the form of *outbursts* (Jenniskens, 1995), caused by trails of material ejected during a previous perihelion passage. Dense trails may typically be found in the vicinity of the comet, producing near-comet outbursts when the comet itself is near perihelion (e.g., 109P/Swift-Tuttle and the 1991–1994 Perseids). Alternatively, older trails or trail segments can produce outbursts by remaining cohesive

within mean motion resonances with the giant planets e.g., the 1998 Leonids (Asher et al., 1999) or the 1945/1986 Ursids (Jenniskens et al., 2002). Both JFCs and HTC's can produce outbursts, the main difference being that JFC-related annual activity is typically weak.

We have computed instances up to 2030 when (a) planet-approaching HTC's return to perihelion (b) planet-approaching JFC's return to perihelion and are physically close to the planet. This is quantified through P-C, the interval in days between the comet and the planet passing through the planetary longitude at which Δ is achieved. These are necessary conditions for a near-comet outburst to occur (Jenniskens, 1995). The calculation is carried out in two steps. First we use the JPL DASTCOM ephemerides to calculate approximate encounter conditions. We then repeat the process using an osculating cometary orbit for the critical epoch generated through numerical integration under the action of planetary perturbations and available through the JPL HORIZONS on-line ephemeris service (Giorgini, 1996). This additional step improves on the work by Christou (2004) and Selsis et al. (2004) by removing a major source of (deterministic) error in the orbit. We have also checked that none of the comets which we discuss here undergo close approaches to the planets prior to these epochs. As far as non-gravitational forces are concerned, the main effect of which would be a change of the P-C quantity, we estimate, based on a Selsis et al. (2004) upper bound of 3 h until 31/12/2015, that our P-C error is no more than 12 h. In any case, trail lengths are usually a few hundred days (e.g., Giacobinids – Rendtel et al., 1995) so even several days' error is not significant.

The results of this procedure are given in Table II. Comet 45P/Honda-Mrkos-Padjusakova is a relatively dust-poor Jupiter family comet (Lamy et al., 1999) that is also the closest Venus-approacher at present. Its orbit

TABLE II
Circumstances of possible near-comet meteor outbursts at Venus and Mars

Comet	Planet	Δ (AU)	v (km s ⁻¹)	P-C (days)	Date
45P	V	0.0017	26	+ 5	9/6/2006
45P	V	0.0101	26	+ 38	30/8/2006
27P	V	0.0389	28	-24	3/7/2011
38P	M	0.0417	13	+ 120	18/3/2019
12P	V	0.0800	53	+ 55	5/6/2024
13P	M	0.0217	27	+ 211	17/11/2024
114P	M	0.0077	11	+ 15	5/10/2026

At those instances the planet may encounter a trail of fresh meteoroids from a previous perihelion passage. Enhanced meteor activity related to Halley-type comets may occur on several planetary years surrounding the comet's perihelion passage. P-C is the interval, in days, between the comet and the planet passing through the critical solar longitude while "date" refers to the epoch when the planet is at that longitude

approaches Venus at two distinct longitudes, once before and once after perihelion (Christou, 2004; Selsis et al., 2004). During its 2006 perihelion passage, the comet will be physically close to Venus on both occasions. This presents an opportunity to observe a venusian meteor outburst as the ESA *Venus Express* spacecraft will be orbiting the planet at that time (Svedhem et al., 2003). The stream encounter geometry is particularly favourable for the August opportunity, where the theoretical stream radiant is near the local midnight direction. The radiant of the June opportunity is near the direction of the Sun thus rendering meteors difficult to observe. An opportunity to observe strong venusian meteor activity associated with a HTC occurs during 27P/Crommelin's 2011 perihelion passage. In analogy to the Earth, increased meteor activity should be expected for a few venusian years surrounding this perihelion passage, with the best opportunity possibly on 3 July 2011, when Venus precedes the comet by only 24 days. The Japanese *Planet-C* Venus orbiter may be still operating within that timeframe (Nakamura and Imamura, 2002). Including meteor observations within its scope of investigations would allow the characterisation of Crommelin-related meteor activity and its variation over the years. Comet 38P/Stephan-Oterma's 2019 perihelion passage provides the first opportunity to observe a meteor outburst at Mars. However, due to the low impact velocity, these meteors may be exceedingly faint (Adolfsson et al., 1996), and thus difficult to detect with methods other than radio/radar. A more favourable opportunity would occur during comet 13P/Olbers' perihelion return in 2024 owing to its higher impact speed on Mars. That same year also sees a possible outburst at Venus related to comet 12P/Pons-Brooks' perihelion return. Finally, an outburst of faint meteors at Mars may occur during comet 114P/Wiseman-Skiff's close approach in October 2026.

The above predictions rely on the comets' osculating orbits at each critical epoch instead of a common epoch of reference (e.g., J2000) to estimate the encounter geometry accurately. Especially in the case of outbursts, however, in order to ascertain whether, and exactly when, a trail will encounter a planet, numerical simulations of trail formation and evolution from past perihelion returns are required. This will be the subject of future work.

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CALCULATION OF VARIABLE DRAG AND HEAT-TRANSFER COEFFICIENTS IN METEORIC PHYSICS EQUATIONS

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Abstract. The conservation of the ablation parameter is one of the main assumptions of the classical physical theory of meteors (PTM). But this value does vary dramatically on meteoroids trajectories for the most part of them. The drag and heat-transfer coefficients in the basic equations of PTM are considered from the gasdynamical point of view and mathematically modeled in the present paper. Analytical approximations of the drag and heat transfer coefficients valid for any flow regimes and separate approximation of the drag coefficient for free-molecule regime are offered and discussed. They use the Reynolds number as the main parameter characterizing flow regimes. The variations of coefficients result in the variation of the ablation parameter by 100% for meteoroids, passing all the flow regimes. The importance of correct calculation of the coefficients for meteoroids motion modeling was demonstrated by the numerical examples.

Keywords: Meteoroids, drag coefficient approximation, heat transfer coefficient approximation, free-molecule flow regime, continuum flow regime

1. Introduction

The classical physical theory of meteors (PTM) (Bronshten, 1983) and many modern works assume conservation of the ablation parameter $\sigma = C_H/QC_D$ that, in fact, implies conservation of specific heat of ablation Q , drag C_D and heat transfer C_H coefficients of meteoroids. By definition the values of $C_D/2$ and C_H are, respectively, the fraction of the momentum and energy of the oncoming flow transferred to the body. Therefore they depend essentially on the realizing flow regime, which, in turn, is highly dependent on body size. So, there are small particles, which move only in free-molecule regime and large bodies, which move in continuum regime. In general case the range of gasdynamic flow regimes over meteoroids changes from free-molecule in upper atmosphere to continuum with boundary layer at low altitudes. Frozen, non-equilibrium and equilibrium chemical regimes are realized on meteoroids trajectories. The heat transfer to the body consists of convective and radiative parts, which may be of different order of magnitude depending

on the flow conditions. Thus, the drag and heat transfer coefficients are multivariable functions varying considerably. Strictly speaking, the problem of these dependences search must be formulated in the framework of the multicomponent flow over some body; it is described by the Navier-Stokes equations and the equation of radiative transport. The solution of mentioned set of equations is time consuming even for modern computers. Besides, it gives the sought quantities at a particular free stream condition, that is, in a particular point of the trajectory of the body moving with given velocity. But ready values of the drag and heat transfer coefficients are required in meteoric problems. So, it is rather topical to find some dependencies of the coefficients on the defining parameters and to express them in analytical form. The present work is devoted to the discussion of existing and new approximations of the drag and heat transfer coefficients and their application to the calculations.

The first contribution to this problem is the work of D.O. ReVelle (ReVelle, 1976) where these coefficients were presented as functions of the Knudsen number. But determining the Knudsen number represents a separate and not so simple problem, and the functions mentioned were given as a set of formulas, fitting the numerical and observational data. In the present work the Reynolds number is used as the main parameter, which characterizes the flow regime; gas dynamical considerations are involved.

The following definition of the Reynolds number is used here: $Re = \rho V r / \mu(T_0)$, where ρ is the free-stream density, V – meteoroid velocity, r – its radius, $\mu(T_0)$ is the air viscosity, calculated with the stagnation temperature $T_0 = T(1 + \frac{\gamma-1}{2} Ma^2)$, T – free stream temperature, γ is the ratio of specific heats, Ma – the Mach number, $\mu(T_0) = \mu \cdot (T_0/T)^\omega$, $\mu = 1.7 \times 10^{-5}$ Pa s, ω depends on the model of air molecules interaction potential.

2. The Drag Coefficient

The free-molecule C_D^{fm} and continuum C_D^c limits of the drag coefficient for meteoroids are well known in classical PTM (Bronshten, 1983). The former is determined by the nature of the particle-surface interactions, the latter depends on the body geometry. The approximation for the transitional regime, which includes these limit cases, was offered and analyzed in (Khanukaeva, 2003). It has the following form:

$$C_D = C_D^c + (C_D^{fm} - C_D^c) e^{-aRe^2}, \quad (1)$$

where $a=0.001$ is the free constant, found on the basis of experimental data (Kussoy and Hortsman, 1970).

Approximation (1) allows an analytical solution of the drag equation for the case of $\omega = 0.5$ in the expression for the viscosity. The analysis of that solution was made in (Khanukaeva, 2003). For large bodies generating bolides it has demonstrated negligible (less than 1%) difference between the velocities calculated with variable and constant drag coefficient. And this coefficient variation gives more than 10% correction to the dynamics of particles of less than 20–30 microns in size.

In addition to the above, the effect of sputtering, being much discussed today, also affects micrometeoroids deceleration in the upper layers of the atmosphere. Though the velocity of the sputtered mass is less than the thermal velocity corresponding to the evaporation temperature (Stanukovich, 1960), the resulting recoil momentum is larger in comparison with the case of molecules outbreak. Therefore the process leads to the growth of the deceleration and may be expressed in terms of the drag coefficient increase (Stanukovich, 1960):

$$C_D^{fm} = 2 + \frac{\sqrt{2Q_*}}{2V} \left[\sqrt{\frac{M_{mat}}{2M_a}} + \left(\frac{V^2}{2Q_{vap}} + \frac{9}{4} \frac{Q_{vap}}{Q_*} \right) \right], \quad (2)$$

where $M_a = 29 \text{ g mol}^{-1}$ – air molecular weight, Q_{vap} – effective enthalpy of evaporation, Q_* – effective enthalpy of “crashing” of meteoroid lattice material with molecular weight of M_{mat} . Using approximation (2) one can obtain an analytical solution of the drag equation in free-molecule regime (Khanukaeva, 2003).

Approximation (2) can be used as a limit expression in approximation (1) instead of the traditional constant value of 2. Such a dependence of the drag coefficient on the Reynolds number is presented in Figure 1. It was obtained in the process of numerical computation of a meteoroid deceleration with the following parameters: $M_{mat} \approx 2M_a$, $Q_* \approx 0.6 \text{ km}^2 \text{ s}^{-2}$, $Q_{vap} \approx 8 \text{ km}^2 \text{ s}^{-2}$,

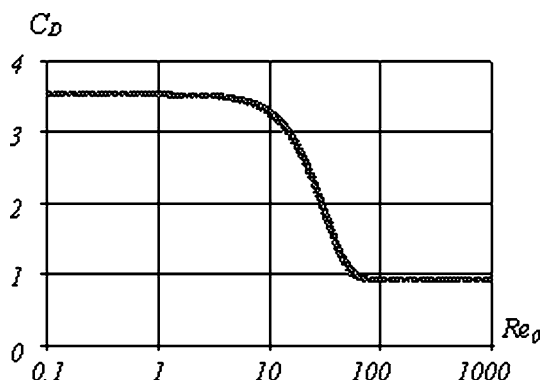


Figure 1. The result of numerical calculation of C_D according to (1) with C_D^{fm} defined by (2).

$T = 284 \text{ K}$, $\gamma = 1.4$. The initial velocity of 35 km s^{-1} was used. For faster bodies the increase of the value of C_D^{fm} will be higher. Approximation (1) is valid for any Reynolds numbers from the very small, corresponding to the free-molecule regime, to the infinite limit, indicating the continuum flow. This universality makes it very convenient for the application to the meteoroids' deceleration description.

3. The Heat Transfer Coefficient

Heat transfer to a meteoric body is calculated here as a simple sum of convective C_{Hcon} and radiative C_{Hrad} components. The search of universal approximations for each of them is hardly a solvable problem, because they vary in several orders of magnitude on meteoroids trajectories and depend on many factors. Still the efforts are being done. The general scheme is the following: (1) approximation of the coefficient in the stagnation point of the body; (2) approximation of heat flux distribution over the body surface; (3) taking into account the vapor shielding effect.

The review of the problem of radiative heat fluxes calculations can be found in (Piluygin and Tirskey, 1989; Stulov et al., 1995) and it cannot be seen as promising for meteoric problems. The approximations existing for the coefficient in the stagnation point are valid only for the restricted intervals of velocities, bodies' sizes and air densities. It was found out that the distribution over the body surface to depend weakly on the body size and to depend very strongly on the body velocity. The dependence was formulated in (Apshtein et al., 1986) as follows $C_{Hrad} = C_{Hrad}(0) \frac{\int_{\Sigma} \cos^n(V) \varphi ds}{S}$, where φ is the meridian angle, S is the cross-section area, $C_{Hrad}(0)$ is the value of the coefficient in the stagnation point, $n(V) = 1.811 + 1/(0.051V - 0.43)$ is the approximation parameter. The existing methods of the vapor shielding consideration are also applicable only to several specific cases.

The approximations of the integral radiative heat transfer coefficient, developed in (Baldwin and Sheaffer, 1971; Suttles et al., 1974; Biberman et al., 1979), demonstrate acceptable correlation only for moderate velocities ($15\text{--}40 \text{ km s}^{-1}$) at altitudes from 40 to 70 km. The discrepancy at lower altitudes is more significant the higher the velocities. Figure 2 represents the comparison of these results for two different velocities.

The review of numerical solutions of radiation gas-dynamics problems, including non-equilibrium radiation can be found in (Park, 1999). Though the accuracy and complexity of numerical solutions are rather high they are not formulated as analytical expressions for the coefficient or for the heat transfer and, thus, cannot be introduced in PTM equations. And even the

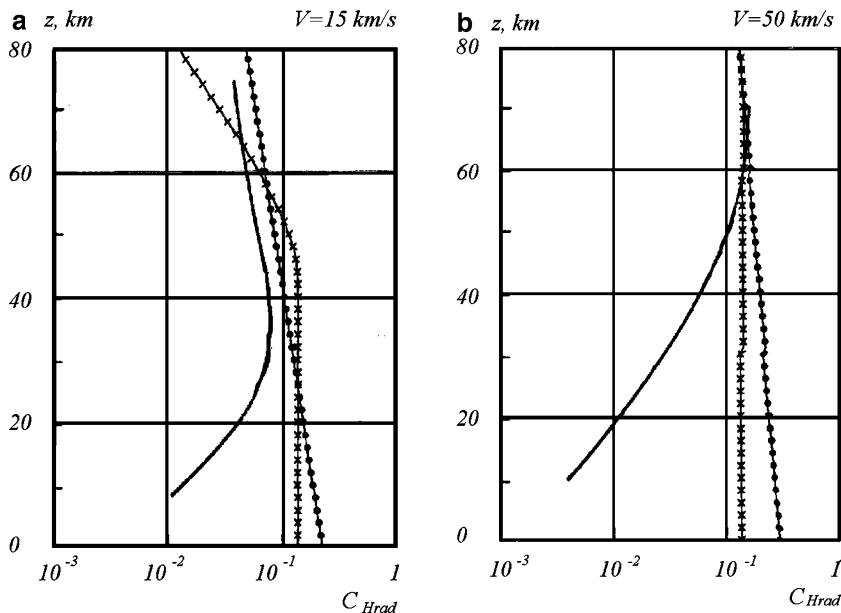


Figure 2. The change of C_{Hrad} with height, according to approximations of Baldwin and Sheaffer, 1971 (x), Suttles et al., 1974 (●) and numerical computations of Biberman et al. (1979) (—).

existing approximations are rarely applied. So, the problem of adequate modeling of radiative heat transfer coefficient for meteoric bodies is opened.

Better success is achieved in convective heat transfer modeling. Shielding effect was considered and formalized for the first time in (Adams, 1959). It may be expressed in terms of the effective enthalpy of ablation or as a correction to the very coefficient value. The distribution over the surface depends neither on body size, nor on its velocity and for a sphere looks like (Murzinov, 1966) $C_{Hcon} = C_{Hcon}(0) \frac{\int_{\Sigma} \cos^2 \varphi ds}{S}$, $C_{Hcon}(0)$ is the value of the coefficient in the stagnation point. The last quantity has been approximated separately in the continuum and free-molecule regimes in many works. Here it is offered the universal dependence of $C_{Hcon}(0)$ on flow conditions as a function of Reynolds number defined above:

$$C_{Hcon}(0) = b/\sqrt{Re} + \left(1 - C_{Hrad} - b/\sqrt{Re}\right)e^{-cRe^2}, \quad (3)$$

where $C_{Hcon}^{fm} = 1 - C_{Hrad}$, as the total heat transfer coefficient is equal to unity (Bronshen, 1983) in the free-molecule limit; and for continuum limit $C_{Hcon}^c \sim 1/\sqrt{Re}$, the approximation known in boundary layer theory. Free coefficients b and c have been determined to fit the numerical data, collected in (Alexandrov, 2003).

The effect of chemical regime change on the convective heat transfer was investigated in many papers devoted to spacecrafts entries. The correction of heat flux due to chemical reactions comes to 30%. This question pertaining to meteoric problems has been considered in (Khanukaeva, 2004). The study demonstrated the accuracy of formula (3) within 30%, and it confirms its sufficient efficiency.

The importance of the adequate heat transfer coefficient modeling is demonstrated by Figure 3. Figure 3a represents the curves of mass change with height, obtained with constant and variable values of C_H for the parameters of Vitim bolide (entrance velocity $V_e = 15 \text{ km s}^{-1}$, entrance angle $\theta = 34.3^\circ$, density $\delta = 3500 \text{ kg m}^{-3}$, entrance mass $M_e = 5 \times 10^4 \text{ kg}$). The convective heat transfer coefficient (Figure 3b) was calculated according to formula (3) (it is worth mentioning here, that $C_{H\text{con}} = C_{H\text{con}}(0)$ for a spherical shape), approximation of (Suttles et al., 1974) was used for the radiative heat transfer coefficient (Figure 3c). Total coefficient (Figure 3d) is obviously far from being constant.

4. Conclusion

The problem of ablation parameter variation on meteoroids trajectories was discussed. The influence of gasdynamic flow regimes on the coefficients was modeled in the form of the dependences on the Reynolds number. There are other factors affecting the drag and heat transfer to meteoroids, such as fragmentation effects, body surface temperature variation, the specifics of gas molecules interactions model, in particular, more realistic values for ω instead of 0.5 used in the present work. They were assumed to be of secondary

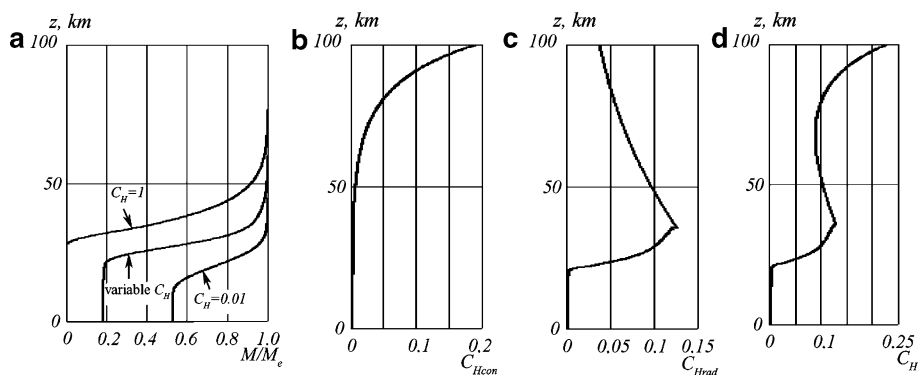


Figure 3. Changes of mass and heat transfer coefficients with height for Vitim bolide parameters.

importance and were not considered in the present work. They may be taken into account in future investigations.

The main conclusion is that the assumption of $\sigma = \text{const}$ is too strong. The approximations of acceptable accuracy were offered for the drag and convective heat transfer coefficients. They are valid for any gasdynamic flow regime and presented in forms convenient for the exploitation. Analytical and numerical solutions of drag and ablation equations of PTM were obtained. The analysis has demonstrated that the variation of the drag coefficient is essential only for small particles, while the variation of the heat transfer coefficient is very significant for any meteoroids.

The existing approximations for the radiative heat transfer coefficient are seemed to be inadequate for meteoric conditions. So the detailed studies in the field of radiative gas dynamics for meteoric velocities may be useful.

Acknowledgement

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RECENT ADVANCES IN BOLIDE ENTRY MODELING: A BOLIDE POTPOURRI*

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Abstract. In this paper, we will review recent research on numerous aspects of bolide entry into a planetary atmosphere, including such topics as the entry dynamics, energetics, ablation, deceleration, fragmentation, luminosity, mechanical wave generation processes, a total (panchromatic) power budget including differential and integral efficiencies versus time, etc. Fragmentation, triggered by stagnation pressures exceeding the bolide breaking strength, has been subsequently included in either a collective or non-collective wake behavior limit. We have also utilized the differential panchromatic luminous efficiency of ReVelle and Ceplecha (2002) to compute bolide luminosity. In addition we also introduce the concept of the differential and integral acoustic/infrasonic efficiency and generalized it to the case of mechanical wave efficiency including internal atmospheric gravity waves generated during entry. Unlike the other efficiencies which are assumed to be a constant multiple of the luminous efficiency, the acoustic efficiency is calculated independently using a “first principles” approach. All of these topics have been pursued using either a homogeneous or a porous meteoroid model with great success. As a direct result, porosity seems to be a rather good possibility for explaining anomalous meteoroid behavior in the atmosphere.

1. Introduction and Overview

This paper is an outgrowth of an invited talk with Dr. Zdenek Ceplecha of the Ondrejov Observatory in the Czech Republic and was presented at the Meteoroids 2004 conference at the University of Western Ontario in London, Ontario, Canada. Since most of the second half of the material that was presented in London was on advances in bolide observational analyses that has already been published as a major paper in Meteoritics and Planetary Science (Ceplecha and ReVelle, 2005), we jointly decided that ReVelle would prepare all of the materials for the invited talk to be published in Earth, Moon and Planets.

There have been several recent advances in bolide entry modeling by ReVelle (2001a, b, c, d, e), in ReVelle and Ceplecha (2001f, g) and also in ReVelle (2002a, b), in ReVelle and Ceplecha (2002) and in ReVelle et al. (2004). These advances include a fragmentation and luminosity model of bolide entry based on an energetics end height approach, a detailed power

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balance calibration during entry within a panchromatic pass-band and the concomitant evaluation of numerous differential as well as integral efficiencies for all major processes that are known to occur. In addition to the earlier proposed extremes of collective versus non-collective wake behavior, a new fragmentation mechanism involving the oscillation between collective wake and non-collective wake extremes has also now been proposed as well. We will systematically present all of these advances within this article.

1.1. HYPERSONIC ENTRY BEHAVIOR AND METEORS AS INFRASONIC SOURCES

Using conventional dimensional analysis more than a dozen dimensionless combinations of similarity parameters naturally arise for the analysis of hypersonic entry into a planetary atmosphere. Fortunately at any one time usually only about four to six of these appear to be important for any specific entry that we have already modeled. The expected aerodynamic characteristics include a large Reynolds number and a large Mach number in a hypersonic flow regime with strong shock waves and shock front radiation from a region of very high temperatures. These values are consistent with a rather small classical Knudsen number (continuum flow regime), but at high altitudes where the neutral gas mean free paths are quite large for smaller bodies, the opposite extreme of free molecular flow can also be evident. Additional numbers are discussed in Ceplecha et al. (1998).

The modern starting point for entry modeling is the classical single-body, stagnation point ablation, *ballistic* entry analysis. This is a wave drag dominated regime for a blunt body with negligible lift and thermal conduction into the interior. For large entry speeds compared to the escape velocity, line sources/modified line sources energy deposition occurs for sufficiently large bodies (see below with regard to the differential acoustic efficiency evaluation however). For a non-linear blast wave relaxation radius from a “small” source, small compared to the density scale height, infrasonic and more generally acoustic-gravity waves (AGW’s) are radiated from the line source and these signals propagate to great ranges due to low atmospheric absorption effects. The blast radius is defined as the square root of the energy deposited per unit length along the trail divided by the ambient pressure at any height. This can also be expressed as the product of the Mach number and the bolide diameter with a numerical multiplying factor, k (generally k is <5 – 10) due to fragmentation effects.

For blast radii $<\sim 10$ m, sound wave absorption by processes in the upper atmosphere is severe and infrasonic signals are very unlikely to be recorded at ground level. Bolides previously detected infrasonically range in blast radius from 10 m to ~ 6 km (with the latter value indicative of the Tunguska bolide – see below) and for corresponding source energies from $\sim 10^{-5}$ kt to ~ 10 Mt.

The wavelengths of the infrasound generated at $x=10$ (at a radial distance = 10 blast wave radii from the source) are ~ 2.81 blast wave radii and beyond $x=10$ the wave propagates as a weak shock disturbance while for downward propagation eventually decaying to a linear perturbation as an infrasonic wave. The waves radiated beyond $x=10$ are influenced by the refractive effects due to the instantaneous atmospheric sound and horizontal wind speed structure as defined at moderate ranges by Snell's Law of Acoustics. The line source blast wave analogy is precisely defined for a body traveling with $Ma \gg 1$ and $dV/dt \equiv 0$, where V is the instantaneous meteor velocity and the resulting energy deposition is within a cylinder. This results in a Mach cone whose half angle is exactly zero as if the body had infinite speed. In fact the predicted refraction can be quite sensitive to this Mach cone half angle if the entry angle is fairly steep, depending on the atmospheric structure at the time of entry.

1.2. BOLIDE PROPERTIES

The nominal properties of the various groups that have been previously identified are conveniently plotted below in Figure 1 in the form of a property diagram following group designations by Ceplecha et al. (1998) using a single-body model of homogeneous meteoroids with $\mu = 2/3$.

In addition, as shown by ReVelle (1983, 2001e, 2002a, b), there is also the question of whether some of the extreme end height behavior witnessed in the atmosphere is due to the fact that the entering particles are moderately or even highly porous (such as the Tagish Lake meteoroid/meteorites for example). This end height behavior is considered to be extreme in the sense that a 30 km end height difference is readily apparent for bodies whose parameters are otherwise identical (mass, velocity, shape, entry angle, etc.) with the exception of the statistical bolide group designation. This progressive increase in end height behavior increases steadily for Group I (ordinary chondrites), to Group II (carbonaceous chondrites) to Group IIIA and finally to group IIIB (strong and weak cometary materials respectively). The uniform bulk porosity values originally inferred by ReVelle (1983, 2001e, 2002b) directly from the U.S.A. Prairie Network flight data range from 50% (for Group II), 75% (for Group IIIA) to 91% (for Group IIIB). Since numerous spectra of the meteor showers indicates that the "toughest" Geminids are virtually identical in composition to the very weakest "Draconids", then a very natural way of describing these bodies is through their degree of porosity. We have also examined the form of this property diagram for porous bodies and have found that it is extremely similar to the results indicated in Figure 1.

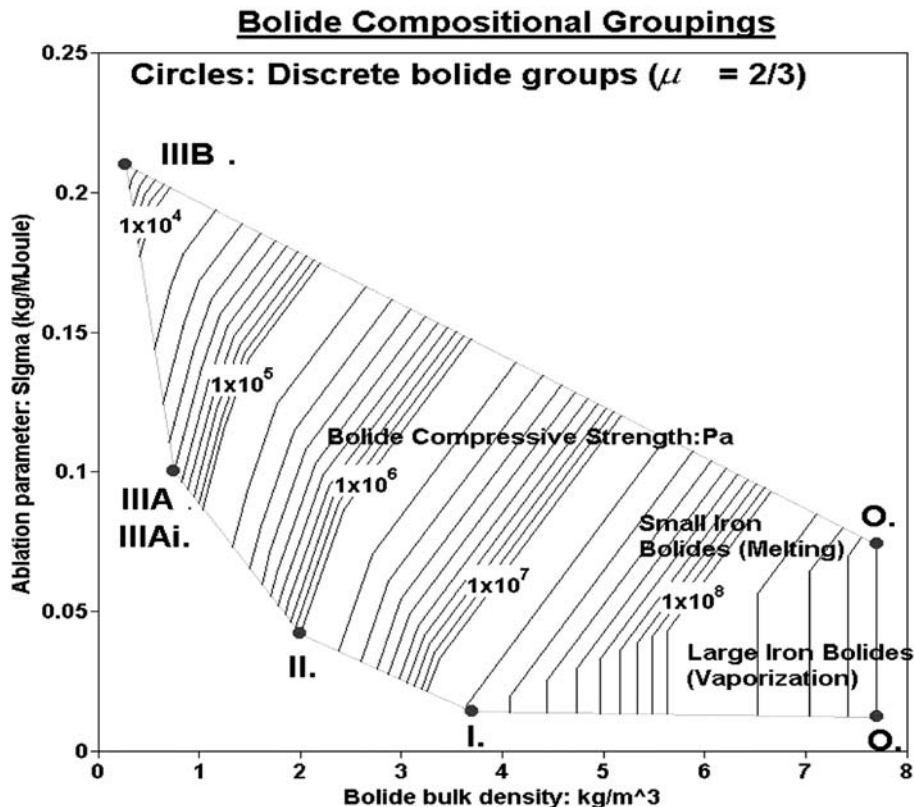


Figure 1. Bolide property diagram, i.e., values of the bulk density (kg/m^3) versus the mean ablation parameter (kg/MJ) during entry as a function of contoured values of the breaking strength (Pa) for meteoroids which were assumed to be homogeneous in their density.

As is discussed in detail subsequently below, an extended version of our original single-body, radiative-hydrodynamic entry model simulation (ReVelle, 1979) has been modified into an energetics format and is shown to be equivalent to the classical drag dominated, constant sigma solution approach derived in the Appendix A (using the appropriate D parameter for the specified level of kinetic energy remaining at the end height). This new energetics model was subsequently used along with a triggered progressive fragmentation model (with stagnation pressure as the mechanical triggering mechanism) and a panchromatic luminous emission model as described in this paper and in ReVelle (2001a–2001e) and ReVelle (2002a). In this work the ablation parameter is fully a function of height and of the corresponding classical Knudsen number for the case of local heat transfer to the body (for more details see below).

2. Mathematical/Physical Entry Model

2.1. ATMOSPHERIC MODEL TYPES

In our modeling we have systematically investigated four specific entry cases, namely a constant or a height variable ablation parameter solution (using the σ parameter) with either a hydrostatic, isothermal model or a fully non-isothermal, hydrostatic model atmosphere that reproduces the U.S. Standard Atmosphere series in middle latitudes in summer and in winter. Input variables include surface values ($z=0$) of the air temperature, sound speed, mean free path, air pressure and then air density can be calculated from the ideal gas law.

These separate cases are all linked to the full physics solutions including ablation, deceleration, fragmentation and panchromatic luminosity, etc. for either a homogeneous or a porous meteoroid model. Atmospheric density and pressure wave variability in the form of turbulence and upward propagating internal gravity waves (IGW) from tropospheric sources are also possible to represent in such models, but will not be reported on here.

It should be noted that there is also a distinct limitation of this approach as applied to other planetary atmospheres. This fundamental limitation is directly due to the fact that the radiative heat transfer coefficient part of the ablation coefficient, σ , has been computed for the typical mean composition, i.e., primarily N_2 and O_2 at altitudes below 100 km, for Earth's atmosphere. A separate radiation code computation would first be required to determine entry values for a large number of bolide radii, geopotential altitudes and velocities so that the results could be curve fit in a manner similar to that in Revelle (1979).

2.2. SINGLE-BODY APPROXIMATION: ENERGETICS FORMULATION

Using standard notation (except as otherwise defined), the end height (where the luminous trajectory ceases) for the case of a single-body is expressed below in the energetics form of ReVelle (1981, 1987, 1993). It is demonstrated in Appendix A that this equation is equivalent to the standard end height equation (ReVelle, 1979). The D parameter of ReVelle expresses the degree to which the original kinetic energy of the body has been removed at the predicted end height with $D=4.605$ corresponding to 99% energy removal and $D=2.303$ corresponding to 90% kinetic energy removal, etc.

2.2.1. *Energetics formulation for the end height: single-body model*

$$z_{KE}(V) = -H_p \cdot \{\ln(p_\infty^*/p_0) \cdot \exp[-(\sigma \cdot F) \cdot V_\infty^2] \cdot \{D - D'\} + \exp[z'/H_p]\} \quad (1)$$

$$z' = -H_p \cdot \{\ln(p_\infty^*/p_0) \cdot (2gH_p/V_\infty^2)\} = \text{Upper boundary condition} \quad (2)$$

$$D' = -\{Ei[(\sigma \cdot F) \cdot V_\infty^2] - Ei[(\sigma \cdot F) \cdot V^2(z)] - \ln(V_\infty/V(z))^2 - [(\sigma/2)(V_\infty^2 - V^2(z))]\} \quad (3)$$

where $Ei(\sigma \cdot F)$ = the exponential integral function; $F = (1 - \mu)/2 = \text{constant}$; σ = ablation coefficient as a function of height; $-2(*) \leq \mu \leq 1$; $\mu = 2/3$ = self-similar value (no shape change); $p_\infty^* = mg \cdot \sin \theta / (C_D A)$ = modified ballistic entry parameter; m = instantaneous meteor mass θ = horizontal entry angle ($> \sim 5$ – 10 degrees using Cartesian coordinates); $p_\infty^* = 4 \cdot \rho_m \cdot r \cdot g \cdot \sin \theta / (3C_D)$ for a sphere; p_0 = surface pressure; r = instantaneous meteor radius; $D = 4.605$ for 99% kinetic energy depletion at the end height

(*) : Effective “pancake” model limits for $\mu < 0$

As discussed in ReVelle (2001a, 2002a), the distinction between the single-body regime and the catastrophic fragmentation limit can be separated on the basis of the ratio of the pressure scale height and the new quantity, the fragmentation scale height:

$$(i) \quad |H_p/H_f| \ll 1 : \text{Single-body model} \quad (4)$$

where H_f = Fragmentation scale height $\equiv -\{A(z)/A_\infty\}/\partial\{A(z)/A_\infty\}/\partial z$; H_p = pressure scale height $\equiv -p(z)/\partial p(z)/\partial z = RT/g$; $A(z)$ = frontal area as a function of height, z ; A_∞ = initial frontal area $p(z)$ = atmospheric pressure as a function of height (ideal gas assumed); $R = R^*/M$ = gas constant for the atmosphere; g = acceleration due to gravity; R^* = universal gas constant; M = mean molecular weight of the air = 28.966 kg/kmol below ~ 85 km.

This limit includes a self-similar ablation solution with no shape change for $\mu \equiv 2/3$. The pressure scale height needs to be replaced by the density scale height in a non-isothermal, hydrostatic atmosphere. For $0 \leq \mu < 2/3$, the solution includes ablation and deceleration, as well as shape change with the frontal cross-sectional area, $A(z)$, decreasing with decreasing height.

Stated simply the fragmentation scale height is simply the vertical distance scale over which the frontal area of the bolide increases by $1/e$ during increasing downward penetration during entry. Since the atmospheric pressure scale height is a measure of the e -folding distance of the atmospheric pressure, i.e., the distance over which the air pressure decreases vertically by $1/e$ as vertical distance above the earth increases, the relevance of a

comparison between these two fundamental vertical lengths scales becomes more readily apparent.

(ii) $H_p/H_f \gg 1$: Catastrophic fragmentation limit (5)

with $\mu < 0$, this solution allows for ablation and deceleration as well as shape change, but $A(z)$ increases with decreasing height. This case encompasses the so-called quasi-liquid “pancake” fragmentation model previously used by numerous authors to model the entry of Shoemaker-Levy 9 into Jupiter’s atmosphere. It has already been shown in ReVelle (2001c) that the fragmentation scale height is a significant parameter (for the conditions expressed above in (5)) that can be readily be derived during an evaluation of the equations for the height of maximum luminosity during entry. Similar comments also apply to other quantities which also reach a maximum during entry such as drag and deceleration, energy deposition, the heating rate, etc.

As shown below in Table I, an additional solution is possible for $\mu > 0$ where the frontal area increases with increasing penetration depth if the fragments act collectively in the wake after they are drawn forward toward the leading fragment (Sepri et al., 1981). This is a clarification from the regime list of ReVelle (2001a). For the single-body approximation with $\mu > 0$, only negative fragmentation scale heights are possible. If the meteoroid has already broken with a leading fragment and $\mu > 0$, it is possible to achieve a small positive fragmentation scale height, but only if there is a strong collective wake behavior among the fragments. The fragmentation scale height is always < 0 if there is a non-collective wake behavior, i.e., if only a rapid transfer of the fragments into the wake with no further interaction with the leading fragment occurs. Intermediate behavior (oscillating periods of collective wake activity) may also produce a positive fragmentation scale height as well and this possibility is currently under investigation. The shape change parameter, μ , cannot yet generally be calculated, except using detailed numerical models. The single known exception is evident in the limit in which velocity is a constant and assuming an H_f/H_p ratio (which the author has derived and already presented at various conferences).

2.3. SIMPLIFIED BREAK-UP MODEL

In our modeling we have allowed bolide break-up triggering into a progressive cascade mechanism only if the stagnation pressure exceeds the tensile/compressive or equivalently the “breaking” strength, T_s , (thermal processes are generally much too slow for the range of thermal conductivities for most observed bolide types. An exception to this may be if the fragments

TABLE I
Summary of known solutions for planetary atmospheric entry as a function of the fragmentation possibilities, the μ parameter, etc

Regimes	μ	Fragmentation	Light	Dynamics
Self-similar: no shape change	$\mu = 2/3$ Classical solution	$ H_f \gg H_p, H_f < 0$	“Normal”- single-body	Radius and area decrease with time or height
Ablation with shape change and deceleration	$2/3 < \mu \leq 0$	$ H_f \gg H_p, H_f < 0$	“Normal”- single-body becoming highly flattened	Radius and area decrease with time or height
Ablation, shape change, deceleration and gross-fragmentation	$2/3 \leq \mu \leq 0$ Fragmented body with collective or non-collective swarm wake behavior	(i) $H_f \gg H_p$, (ii) $H_f \ll H_p, H_f > 0$	Enhanced emission near end height or decreased emission	Effective radius or area increases near end height or effective radius becomes even smaller
“Pancake” catastrophic break-up: lateral stretching	$\mu < 0$ Instability for very large radial growth	(i) $H_f \gg H_p$, (ii) $H_f \ll H_p, H_f > 0$	Single-body: increased end height and light emission	Large radial growth as penetration proceeds

produced are small enough to allow a rapid thermal conduction into their interior during the lifetime of the luminous entry and concomitant ablation process which is generally $< \sim 10$ s).

Fragmentation is much like turbulence, i.e., an unsolved problem and it is unlikely that a single universal approach will work for all bolides. We have assumed a “triggered” progressive fragmentation model and this does seem to work for a number of cases as a cascade of fragments develops much like the description of the cascade during a cosmic ray shower event. However, in a number of studied cases, this method does not seem adequate and single discrete large amplitude fragmentation events can also occur. In such cases we simply limit the number of fragments to a small number $\sim 2-4$ and continue calculating the results with the fragmentation processes subsequently turned off. Additional fragmentation models will also be attempted in the future to determine if a more general fragmentation process can be identified.

The cascade process was assumed to be a simple geometric series of the form $1 \rightarrow 2 \rightarrow 4 \rightarrow 8$, etc. pieces (other simple progressions are also easily input for this part of the fragmentation modeling process however) until some limiting value has been achieved. As will be noted later, this increasing effect is only marginally significant for deceleration, but the final number of fragments produced is extremely sensitive for the luminosity that is predicted. The final number of fragments (if break-up was triggered) was an input to the code and usually varied between 2 and 1000. For specific photographed entries we knew the final number directly from the photographs, otherwise the final number was calculated simply by trial and error estimation between model outputs and actual flight data. The breaking strength has been defined for either a homogeneous body of uniform bulk density (composition) or for a porous body, including possible effects from prior space collisions (macroscopic cracks), etc. We assigned nominal T_s values from uni-axial laboratory test data on meteorite samples using materials from ordinary chondrites to pumice (Baldwin and Sheaffer, 1971, etc.). We assigned a reference strength for each bolide type $= k^* \cdot T_s$ with $k^* = 0.20$ as a nominal value after accounting for weaker structure due to porosity, space collisions, etc. After break-up occurs, we allowed each fragment to be of the same size and computed σ for the main fragment leading the swarm of fragments that are cascading into more fragments while continuing to ablate according to their size. After the body is split into two or more parts, thus decreasing the radius, σ , decreases dramatically (since it is computed for the newly broken, individual leading fragment with a much smaller radius). The gas cap boundary layer can undergo a transition from turbulent to laminar flow as time proceeds and σ will rapidly rebuild due to increased radiative as well as convection/conduction effects and the gas cap can again become turbulent. If the progressive splitting continues and the radius decreases, σ decreases again and the gas cap boundary layer can change from turbulent to laminar once

again, but σ may again rebuild and the gas cap can become turbulent again, etc.

We assumed that there was a rapid wake transfer and thus set a time delay for the fragments to reach the wake and before the start of optical radiation emission ($\ll 1$ s using a simple linear scheme that depends upon the instantaneous speed of the leading fragment). Once the fragments reached the wake, we allowed either a non-collective or a collective wake model to be operative (Sepri et al., 1981). In the former possibility, the fragments continue to ablate and are permanently lost from influencing the deceleration and luminosity at progressively lower altitudes. For the latter possibility the fragments are drawn forward (due to the decreased air pressure behind the main body) toward the leading fragment and act collectively as a flying “swarm” of fragments that determines the future luminosity and deceleration possibilities. It is also possible for this process to repeat on a quasi-periodic basis during entry and this intermediate fragmentation scheme is also currently being investigated. As noted in ReVelle (2002a), this relatively rapid variation of the light curve has been interpreted previously as being due to bolide rotation effects (Beech and Brown, 2000), but according to the above model, it could also be due to changes in the frontal cross-section of the body as fragments sweep into and then out of the near-wake region where significant luminosity is radiated.

Numerous authors have addressed the breakup problem, way too many to summarize in this short review. Many schemes have tried to modify the single-body model to enhance the frontal area for both drag and heat transfer or just for heat transfer, or to hypothesize a turbulent mixing process of the ablated vapor that remains with the body as it continues its subsequent flight, a “quasi-liquid” pancake model of rapid lateral spreading into a very flattened disk, porosity effects, etc. Most schemes have failed to capture the essential physics of what is actually happening during entry. This is one reason why we chose to not only predict the resulting dynamical entry deceleration and drag, but also the simultaneous panchromatic luminosity production.

In this model we have followed the pioneering work of Sepri et al. (1981) and simply allowed the fragments to assemble themselves in a maximum drag orientation fashion (an assemblage of pieces all of the same size that are by assumption flying side by side (so-called “flying buckshot”) as they continue to ablate and fragment. This assumption can only be justified by additional separate numerical simulations suggested in Sepri et al. (1981). Also, as has been discussed previously in ReVelle (2001a, 2002a) this topic is currently a subject of further investigation. The fragmentation process assumed in this analysis of the progressive fragmentation type is not unique and has not found to be in agreement with the entry modeling of all bolide entries studied thus far. It does seem to be a good start at least for a large number of the

numerous modeled bolide events for all of the modeled parameters including both the fragmentation possibilities as well as the panchromatic luminosity.

2.4. MULTIPLE FLOW REGIMES

We can define the following relevant Knudsen numbers of the flow:

- (i) For atmospheric processes:

$$Kn^{**}(z) = \lambda(z)/H_\rho(z) \quad (6a)$$

- (ii) For mechanical wave generation from bolides:

$$Kn^*(z) = \lambda(z)/\Lambda(z) \quad (6b)$$

- (iii) For heat and momentum transfer to bolides:

$$Kn(z) = \lambda(z)/r(z) \quad (6c)$$

where $\lambda(z)$ = neutral gas mean free path, $H_\rho(z)$ = atmospheric density scale height $\equiv \{-\rho(z)/\partial\rho(z)/\partial z\}$, $\rho(z)$ = atmospheric density as a function of height, $\Lambda(z)$ = wavelength of the AGW generated by the bolide, $r(z)$ = radius of the bolide.

The definition of continuum fluid properties is if the classical Knudsen number given by (6c) above is $\ll 1$, whereas the free molecule flow definition occurs for the classical Knudsen number $\gg 1$ (Bronshten, 1983). The conventional theory for heat transfer to the meteor body has consistently used definition (iii) above. Thus, we are proposing a new theory in order to include free molecular flow using (ii) above where Λ = diffuse wavelength of the cylindrical propagating waves ($= k \cdot 2.81 \cdot R_0(z) = 5.62 \cdot k \cdot Ma(z) \cdot r(z)$) that “must eventually pile up at infinity”, unlike the strong blast waves that form uniquely for a continuum flow situation. In the above expression, k is a constant at any height which accounts for non-single-body behavior of the blast wave relaxation radius, $R_0(z)$ and explicitly accounts for fragmentation effects (k is > 1 and usually < 5 in the author’s modeling experience which depends in part on the final number of fragments prescribed) and finally Ma is the body Mach number comparing the instantaneous speed of the leading body against the local adiabatic thermodynamic sound speed, c_s . Since $\Lambda(z) \propto r(z)$, this relation for Kn^* scales directly with Kn in a constant manner and is consistently much smaller than Kn due primarily to the large Mach number of the flow. Thus, we *must* include this term, which involves the

differential acoustic efficiency, in the overall meteor power budget at all heights for almost all sizes of bodies because $Kn^* < O(1)$ even at the lowest penetration heights even though Kn is *not* $O(1)$. Even when $Kn^* \gg 1$, the differential acoustic efficiency is $\ll 1$ already (see below) which is probably why this fact was not recognized much earlier.

Thus, to briefly summarize, even before the classical Knudsen number is sufficiently small compared to unity, the ratio of the neutral gas mean free path to the “diffuse” blast wave wavelength is sufficiently small so that power is being deposited into relevant and propagating atmospheric waves, so that a proper accounting of the power balance demands that this form of power loss be included even for cases where the classical Kn is quite large.

2.5. ENTRY PROCESSES: DRAG, DECELERATION, LUMINOSITY PRODUCTION AND ENERGETICS, ETC.

We have started from a fundamental *ad hoc* assumption, namely that the bolide produced luminosity is proportional to the time rate of change of the kinetic energy of the body (single-body or fragmented), with the proportionality constant being the luminous efficiency factor, τ_L , in the spectral band of interest, i.e., the panchromatic band from ~ 360 – 675 nm (Spurny et al., 2001):

$$I(t) = -\tau_L \cdot dE(t)/dt \quad (7)$$

This assumption is justified on the basis of bolide spectra which show primarily that excited lines due to excited meteor atoms/ions are present with generally only a small contribution from excited atmospheric species at least in a panchromatic pass-band. The luminous efficiency is now available from a refined semi-empirical model (ReVelle and Ceplecha, 2001f, 2002b). We present below an example of our recent successful luminosity modeling effort for the famous Czech bolide, Benesov (May 7, 1991) in Figure 4. This bolide was considered previously by Borovicka and Spurny (1996), Borovicka et al. (1998a, b), etc.

Our present results confirm the previous initial mass estimates for Benesov of ~ 2000 kg while providing far more reasonable estimates of its terminal mass than predicted in previous theoretical modeling studies which were all greater than at least 500 kg. At the same time we have also provided a very reasonable zeroth order fitting of some of the key details of its observed light curve.

2.5.1. Homogeneous versus porous meteoroid modeling

ReVelle (2001e, 2002b) has shown that at the same velocity, mass, entry angle, shape, shape change parameter, etc., porous bolides are far more

efficient light producers than are low porosity bodies. Specifically, light increases compared to non-porous bodies are for Group II (50% porosity) – up to 9 times larger, for Group IIIA (75% porosity) – up to 51 times larger, and for Group IIIB (91% porosity) – up to 225 times larger. The increase in light production is due physically to the fact that the ratio of the kinetic energy changes of a porous body compared to that of a non-porous body increase as the ratio of the square of the heat transfer area compared to the drag area. Consequently, as shown in ReVelle (2001e) the light production increases as the ratio of the square of the ablation coefficient for porous bodies compared to those for non-porous bodies. These values have assumed that all meteor bodies are chondritic in their composition. It has already been demonstrated that for bodies such as the Tagish Lake bolide and concomitant meteorites (Brown et al., 2002), porosity modeling is totally essential in order to correctly match the dynamics, the energetics as well as its luminosity.

Other effects such as bolide rotational influences on the light production are discussed in ReVelle (2002a).

2.6. TOTAL POWER BALANCE: DIFFERENTIAL AND INTEGRAL EFFICIENCIES

Bolide source energies can be estimated in a number of ways. These include various entry modeling (ReVelle, 1979, 1980, 2001a, 2002a) and by using infrasonic/seismic techniques, etc. Most of the infrasonic approaches are listed in ReVelle and Whitaker, (1999). There is also a very promising semi-empirical approach to the amplitude prediction problem combining space-borne sensor detections, used in combination with infrasonic detections, in Edwards et al. (2004 – this issue). Still additional applications of the acoustic differential efficiency approach combined with acoustic-gravity wave conservation (see below) have lead to a new method for very reliably predicting the source properties from satellite or ground-based camera data as well as infrasound and/or seismic detections as well at moderately close ranges (ReVelle et al., 2004).

2.6.1. *Differential and integral efficiencies*

2.6.1.1. *Large bolides: total power budget analyses:* We can perform a power budget analysis at any instant of time or equivalently evaluate the time rate of change of the kinetic energy of the bolide ($\equiv 1/2 \cdot V^2 \cdot dm/dt + mV \cdot dV/dt$), as originally presented in equation (1) of Romig (1965), but that definitely includes the differential acoustic efficiency, ε , (that is discussed further directly below) as long as $Kn^* < O(1)$ as justified earlier in Section 2.4. Multiple Flow Regimes:

$$P_{\text{tot}} = \sum P_i = P_{\text{heat}} + P_{\text{light}} + P_{\text{sound}} + P_{\text{ionization}} + P_{\text{dissociation}} + \cdots \quad (8)$$

or:

Total power dissipated = thermal power (heat dissipated) + light power + acoustic power + ionization power + dissociation power + ...

Algebraic normalization, at any instant, of this *relative partitioning* of various complex energetics processes produces:

$$1 = P_{\text{heat}}/P_{\text{tot}} + P_{\text{light}}/P_{\text{tot}} + P_{\text{sound}}/P_{\text{tot}} + P_{\text{ion}}/P_{\text{tot}} + P_{\text{diss}}/P_{\text{tot}} + \dots \quad (9)$$

We can identify each of these ratios as the efficiency of the power dissipation for each of the recognized physical processes during entry as:

(1a) Luminous efficiency = $P_{\text{light}}/P_{\text{tot}}$ (over optical wavelengths); or: (1b) radiative efficiency = $P_{\text{radiation}}/P_{\text{tot}}$ (over all wavelengths); (2) Acoustic efficiency = $P_{\text{sound}}/P_{\text{tot}}$; (3) ionization efficiency = $P_{\text{ion}}/P_{\text{tot}}$; (4) dissociation efficiency = $P_{\text{diss}}/P_{\text{tot}}$; Here we have *not* differentiated between the dissociation of the air molecules and that of the meteoric vapor itself in this zeroth order energetics evaluation process.

These are *differential* efficiencies at any point along the entry path.

This evaluation process was initially described by Opik (1958) and Romig (1965) with respect to the reference frame of the moving bolide for free molecular flow in the form: "the relative kinetic energy of the intercepted air particles is transferred to the body in the form of heat and the materials ejected from the surface produced light and ion pairs upon collision with ambient air particles". Obviously the complexity of continuum flow and additional aerodynamic regimes are far more complicated to evaluate reliably, but we seem to be doing a reasonable job of evaluating all of the known processes, with the exception of a few "small" omissions discussed directly below.

In this preliminary power budget result not all physical processes have yet been included, i.e., some of the neglected processes include: Atmospheric internal gravity wave excitation, infrared and microwave luminosity production, surviving meteorite fragment kinetic energies, etc. For this reason the sum of the algebraic expression in (9) above should sum to unity only approximately. This procedure was developed primarily as a theoretical zeroth order guide purely to examine if the principle energetics components modeled during entry were being satisfactorily accounted for such that a gross omission of an energetics source (or sink) term was being overlooked.

2.6.1.2. Differential acoustic efficiency definition: The near-field differential acoustic efficiency, ε , can be evaluated by forming the ratio of the weak shock, acoustic wave kinetic energy density (at $x=10$) compared to the bolide kinetic energy density deposition into the non-linear volume defined at

$x=1$, where $x \equiv R/R_0$, R =slant range from the bolide and R_0 is the line source/modified line source blast wave relaxation radius all as a function of the geopotential height, z (approximately equal to the geometric height within ~ 1 km, below about 80 km).

Let:

$\varepsilon \equiv$ wave kinetic energy density/kinetic energy transferred into the non-linear deposition volume

$$\varepsilon(z) \equiv 1/2 \cdot \rho(z) \cdot \Delta u^2(z) / \{1/2 \cdot m(z) \cdot V^2(z) / \{\pi \cdot R_0^2(z) \cdot l(z)\}\} \quad (10)$$

$\Delta u = \Delta p(z) / \{\rho(z) \cdot c_s(z)\}$ for plane acoustic waves – wind due to the wave
 $p(z)$ =ambient pressure as a function of altitude, $\rho(z)$ =ambient air density as a function of altitude, $l(z)$ =line source length as a function of altitude, $l(z) \equiv (z' - z) / \sin \theta$; ε is evaluated at $x=10$ ($=10 \cdot R_0$ from the entry trajectory) where $\Delta p(z) = 0.0575 \cdot p(z)$ from “first principles”, theoretical numerical line source pressure wave calculations as discussed in ReVelle (1976, 2002a) and

see also further details below.

We can also perform a units analysis for ε to show that as defined it is dimensionless and write this expression out in the scaled form:

$$[\varepsilon] = (1/\gamma^2) \cdot \{(\rho(z)/\rho_m) \cdot (V(z)/c_s(z)) \cdot (l(z)/(R_0(z)))\} \quad (11)$$

Specific final numerical values are as follows:

$$\varepsilon = k' \cdot p^2(z) \cdot l(z) \cdot V(z) / (\rho(z) \cdot \rho_m \cdot c_s^5(z) \cdot R_0(z)) \quad (12)$$

where $k'=0.0198$ as evaluated for $x=10$ (or $k'=0.0163$ for $x=5$).

The evaluation of k' is to be accomplished where the waves are quasi-linear so that non-linear effects are sufficiently small (very small amplitude, etc.) as indicated in ReVelle (1976). The first position for which this is the case, is at $x=10$ (with a slight x dependence noted for the value of k').

To evaluate the general case of acoustic-gravity wave efficiency including IGW (see also Section 3 below) we have derived results from additional information in Mihalas and Weibel-Mihalas, 1999) with γ =the ratio of the specific heat at constant pressure to that at constant volume for air (considered as an ideal diatomic gas $\cong 1.40$):

$$\Delta u = [c_s^2 \cdot K_x / (\gamma \cdot \omega)] \cdot [\{\Delta p/p_0\}]; \quad \omega = 2 \cdot \pi \cdot f; \quad K_x = 2 \cdot \pi / \lambda_x \quad (13)$$

where K_x =horizontal wavenumber of the wave, ω =angular wave frequency $= 2\pi \cdot f$, f =linear wave frequency, λ_x =horizontal wavelength.

This is clearly a topic for further research in order to compare results against the work of Golitsyn et al. (1977) – see below in Section III for further details.

2.6.1.3. *Definition of the integral acoustic efficiency:* ε_{int} = acoustic kinetic energy density/(initial kinetic energy/total volume of energy deposition)

$$\varepsilon_{\text{int}} \equiv 1/2 \cdot \rho(z) \cdot \Delta u^2(z) / \{1/2 \cdot m_{\infty} \cdot V_{\infty}^2 / \{\pi \cdot R_{0\infty}^2 \cdot l_{\infty}\} \} \quad (14a)$$

$$\varepsilon_{\text{int}} \equiv k' \cdot \{p^2/(\rho(z) \cdot c_s^5(z))\} \cdot \{l_{\infty}/R_{0\infty}\} \cdot \{V_{\infty}/\rho_m\} \quad (14b)$$

where once again $k' = 0.0198$ as evaluated for $x = 10$.

2.6.1.4. *Differential and integral acoustic efficiency: their relationship*

$$\varepsilon/\varepsilon_{\text{int}} = 1/2 \cdot \rho(z) \cdot \Delta u^2(z) / \{1/2 \cdot m(z) \cdot V^2(z) / \{\pi \cdot R_0^2(z) \cdot l(z)\} \} / [1/2 \cdot \rho(z) \cdot \Delta u^2(z) / \{1/2 \cdot m_{\infty} \cdot V_{\infty}^2 / \{\pi \cdot R_{0\infty}^2 \cdot l_{\infty}\} \}] \quad (15a)$$

$$\varepsilon/\varepsilon_{\text{int}} = k' \cdot p^2(z) \cdot l(z) \cdot V(z) / (\rho(z) \cdot \rho_m \cdot c_s^5(z) \cdot R_0(z)) / [k' \cdot \{p^2(z)/(\rho(z) \cdot c_s^5(z))\} \cdot \{l_{\infty}/R_{0\infty}\} \cdot \{V_{\infty}/\rho_m\}] \quad (15b)$$

$$\varepsilon(z_{\text{end}})/\varepsilon_{\text{int}} = \{l(z_{\text{end}})/l_{\infty}\} \cdot \{V(z_{\text{end}})/V_{\infty}\} \cdot \{R_0(z_{\text{end}})/R_{0\infty}\} \quad (15c)$$

So far in our panchromatic pass-band power budget analyses we have not specifically included either the infrared or the ultraviolet radiative emission from bolides or the microwave electrophonic/ethaerial sound emission or the internal gravity wave differential efficiency, or the efficiency corresponding to the kinetic energy of the surviving fragments, etc. The ultraviolet emission is very important however, but has been implicitly included already in our analysis since the ablation calculations (through $\sigma(z)$) have specifically included the radiative heat transfer from the very strong leading shock front. Since our “total” power balance (see below) is so close to 100% at low heights, it is unlikely that the other differential efficiencies are generally very large. The electrophonic/ethaerial microwave source is known to be very small for example.

2.6.1.5. *Differential/integral luminous efficiency definition:* This differential luminous efficiency is defined as the optical luminous power (Watts/steradian) as a function of range compared to the time rate of change of the bolide kinetic energy in a panchromatic pass-band: $\sim 360\text{--}675$ nm (with the integral luminous efficiency production being compared to the initial kinetic energy).

The differential luminous efficiency expression developed by ReVelle and Cepelch (2001f) is given in two separate velocity regions and is plotted in

two velocity difference regimes in Figure 2 (near the beginning of the flight) and in Figure 3 (closer to the end of the luminous flight).

We now will determine the generalized relationship between the differential and integral luminous efficiencies (work that originated in ReVelle (1981)):

2.6.1.6. *Differential luminous efficiency values:*

$$I_L(t) = -\tau_L \cdot dE_k/dt \quad (16a)$$

$$\tau_L = -I_L(t)/dE_k/dt \quad (16b)$$

2.6.1.7. *Integral luminous efficiency values:*

$$\int I_L(t)dt = - \langle \tau_L \rangle \cdot dE_k(t) \quad (17a)$$

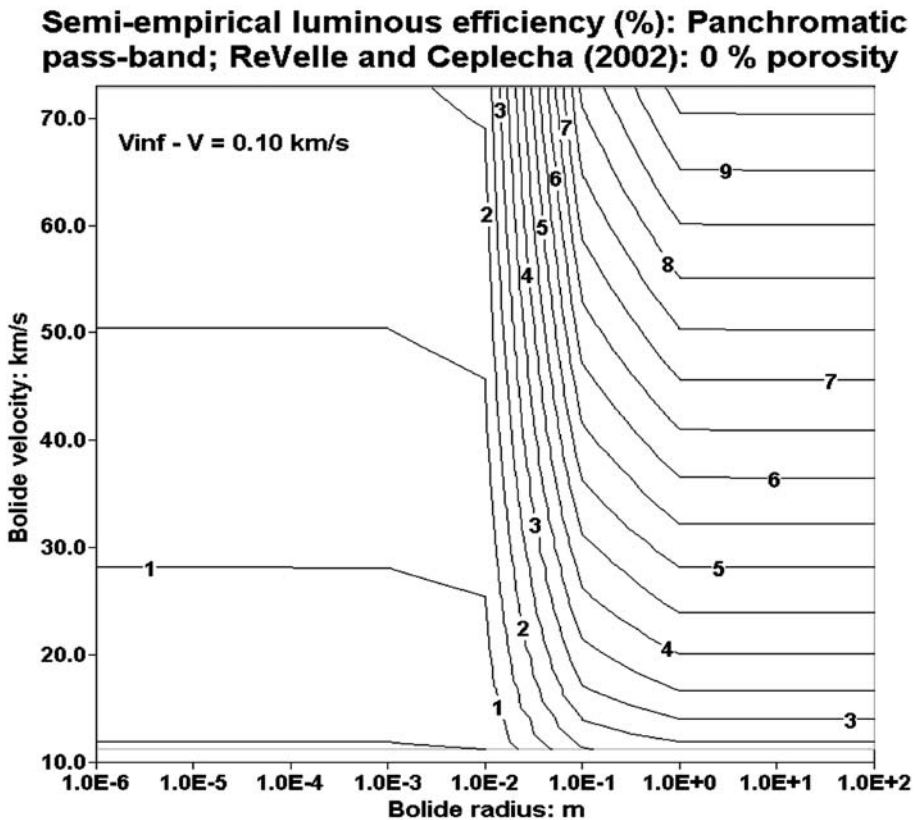


Figure 2. Panchromatic luminous efficiency as a function of mass, air density and velocity near the beginning of the atmospheric trajectory.

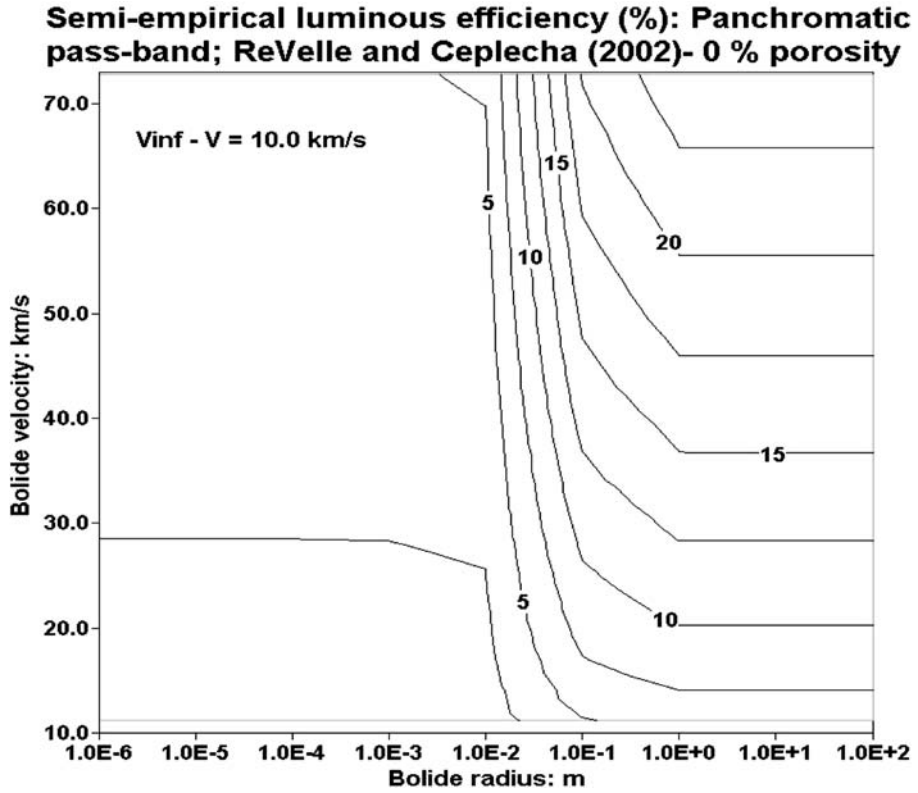


Figure 3. Panchromatic luminous efficiency as a function of mass, air density and velocity near the end of the atmospheric trajectory.

$$\int I_L(t)dt = - \langle \tau_L \rangle \cdot \{0.5 \cdot (m_\infty \cdot V_\infty^2 - m_f \cdot V_f^2)\} \quad (17b)$$

$$\langle \tau_L \rangle = - \int I_L(t)dt / \{0.5 \cdot (m_\infty \cdot V_\infty^2 - m_f \cdot V_f^2)\} \quad (17c)$$

2.6.1.8. Generalized final results:

$$\tau_L / \langle \tau_L \rangle = \left\{ I_L(t) / \left[2 \cdot \int I_L(t)dt \right] \right\} \cdot \left\{ (m_\infty \cdot V_\infty^2 - m_f \cdot V_f^2) / dE_k/dt \right\} \quad (17d)$$

and where the integration limits in (17a)–(17c) are over the visible duration of the bolide, i.e., $t=0$ at $z=z'$ to $t=t_{\text{end}}$ at $z=z_{\text{end}}$ where z_{end} is the lowest height where luminosity has been registered by the photographic emulsion

Benesov Bolide: May 7, 1991: Collective Wake Behavior

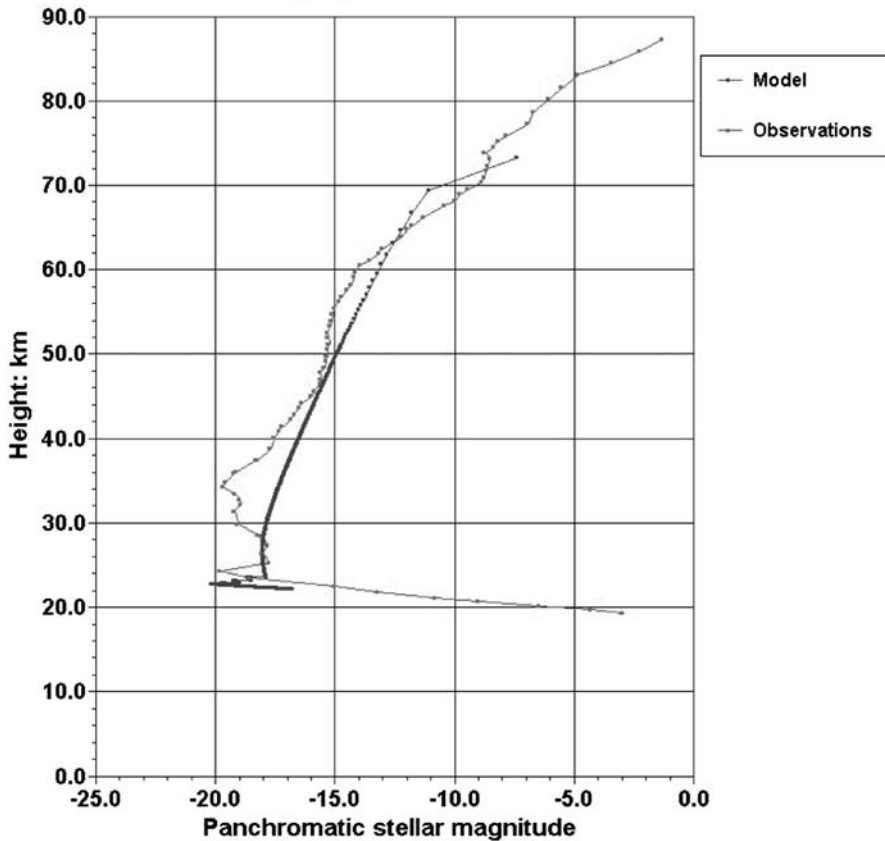


Figure 4. Example of panchromatic luminosity modeling prediction for Benesov (entry parameters assigned: sphere of unchanging shape, initial radius = 0.50 m, Zenith angle of the radiant = 9.4° , initial velocity = 21.8 km/s, uniform volume porosity = 15%, Final number of fragments = 8, collective wake model behavior assumed for an initial mass of = 1647 kg and a predicted terminal mass = 61.02 kg).

(for the case $D = 4.605$, this is also the corresponding height where 99% of the original kinetic energy of the bolide has been removed).

Thus, we can see that there is not a general constant relationship between these two parameters, since each case will depend upon the specific values of mass, degree of porosity, ablation parameter, luminous efficiency, etc.

2.6.2. Total power budget analysis

2.6.2.1. *Evaluation of dimensionless efficiency ratios:* To perform a total power budget for the bolide entry process, we have started our analysis from two detailed and independent sets of results, namely the differential acoustic efficiency discussed above and the semi-empirical, panchromatic differential

luminous efficiency: (ReVelle and Cepplecha, 2001f, 2002c). In order to accomplish the total power budget, we have scaled all of the differential efficiencies, *except* for the differential acoustical efficiency, with respect to the semi-empirical, panchromatic luminous efficiency utilizing data from earlier theoretical and experimental measurements reported in Romig (1965) and utilized in the bolide energetics formulation presented in ReVelle (1980, 1997). Most of these energy scaling estimates were adopted from the synthesis provided by Greenhow and Hawkins (1952), most of which was based on radar and optical luminosity measurements as well as theoretical work at that time by a number of workers, including Opik. The original results of Greenhow and Hawkins were further separated into values of the various differential efficiencies for the extreme limits of “bright” and “faint” meteors. Here we have only utilized the “bright” meteor ratios and modified them in such a way as to optimize the total power budget as best as possible using the simplest possible formulation during the entire entry period.

After many sets of evaluations of these ratios by trial and error, the final, zeroth order and most simplified, normalized set of values utilized in this paper are given by

$$\tau_h/\tau_L = 20.0(*); \tau_i/\tau_h = 0.001; \tau_{\text{diss}}/\tau_h = 0.50 \quad (18a, 18b, 18c)$$

where τ_h = differential heat (thermal) efficiency, τ_i = differential ionization efficiency, τ_{diss} = differential dissociation efficiency (of the entire mixture, i.e., air and meteoric vapor).

(*) Literature values range from ~ 50 to >100 times depending on the brightness of the meteors and the spectral pass-band of the measurements, but in those evaluations, dissociation effects were not explicitly considered.

The ratios used in this paper are of course only an approximation to the “truth” and as acknowledged in the original reference of Greenhow and Hawkins (1952), the individual ratios could be uncertain by $\pm 50\%$. We have provided this evaluation for our entry modeling, so that for a given bolide, an estimate can be made of how well we have accounted for all forms of energy at all heights/times. In this process, we are only using a semi-empirical estimate of the differential panchromatic luminous efficiency and all ratios are scaled to this efficiency with the exception of the differential acoustical efficiency. Although the semi-empirical panchromatic luminous efficiency is very precise and has been constructed to be a function of mass, air density and velocity for all possible altitudes, masses and speeds, it is not perfect in its evaluation of the bolide light emission process which is certainly very complex, especially during fragmentation events. For very low velocity entries for example, the summation of efficiencies above is typically slightly less than unity throughout the entry.

The differential acoustic efficiency was also independently derived from “first principles, i.e., a detailed numerical solution of the fundamental conservation equations for a line source explosion” and was evaluated using the results of Plooster (1968, 1971) for a very high temperature and heavily ionized lightning channel. His modeling work was subsequently applied to pressure wave signals emanating from a low altitude lightning discharge by Jones et al. (1968), i.e., ordinary thunder. However, the differential acoustic efficiency is also subject to the uncertainty of the actual initial conditions present during the generation of line source blast waves at large altitudes typical of bright bolide entry as well. As noted in ReVelle (1976), the decay of the pressure amplitude with range has been written only for the case “ C ” = 1 and “ δ ” = 1 (where “ C ” = Plooster’s adjustable parameter which determines the spatial region in which the transition to a weak shock wave occurs and “ δ ” = efficiency with which line source blast waves are generated in comparison to earlier results by Lin (1954)), etc.

In summing these ratios in a simple power balance, there is also the question of the spectral limits of the evaluation. Here we have limited the results to a panchromatic band (~ 360 – 675 nm), but have appropriately incorporated information from processes occurring outside that spectral band, i.e., the ultraviolet regime for the leading very high temperature shock front and its subsequent effect on meteor ablation processes. For these and additional reasons the summation is only approximate and can at times either exceed or even be substantially less than unity, as evaluated only to zeroth order. For very large sources (very large blast wave radii) the former is almost never the case however, even for the zeroth order ratios and even at quite early times in the entry. The above ratios do appear to be consistently deficient at very early times in the free-molecule flow regime, even for very large bodies however, where the summation can often be as low as only 0.40. We are continuing to evaluate these normalized ratios for the best possible power budget solutions for all sizes, speeds, and corresponding kinetic energies of observed bolides and will report the details of these more precise evaluations at a later time.

An example of the results of computing the total power balance versus time for the entry of the Neuschwanstein meteorite fall (ReVelle et al., 2004) is given below in Figure 5.

2.7. SOLUTION PROCEDURE

In order to solve the above system of equations in a self-consistent manner, we first specified all of the initial values, constants and height variable quantities such as the bolide entry speed, size, shape factor, drag coefficient, D parameter, σ , θ , S_f , μ , etc.

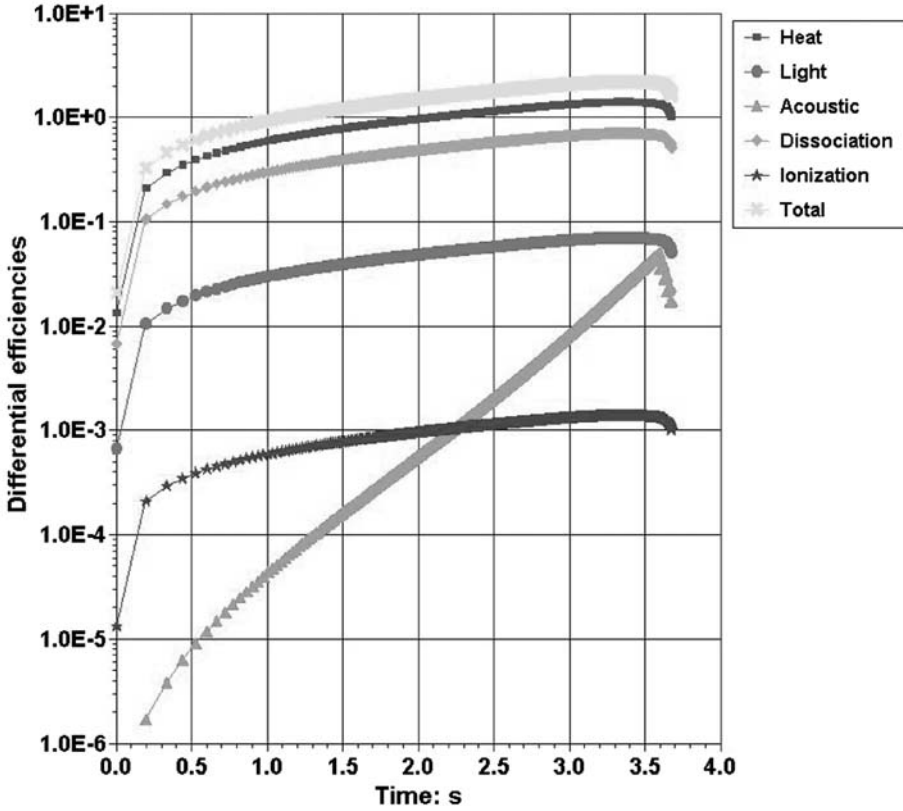


Figure 5. Total power balance in a panchromatic passband versus time for the Neuschwanstein meteorite fall (ReVelle et al., 2004).

Next we solved the transcendental equation of ReVelle (1993) and also presented in Appendix A below for speed at the height corresponding to D ($\equiv$ the end height) with simple ablation theory parameters as a function of the fireball group ($\sigma = \text{constant}$ approximation only). This is given directly below in the form:

$$V(z) = V_{\infty} \cdot \exp[(\sigma/4) \cdot (V_{\infty}^2 - V^2(z))] \cdot \exp[-D/2] \quad (19)$$

This simple equation is perhaps one of the weakest links in the modeling process, but fortunately the final results are not extremely sensitive to this result. It is certainly superior to arbitrarily assigning a velocity below which ablation ceases to the modeling process as has been done by some other authors however (Baldwin and Sheaffer, 1971, etc.).

Next we computed the various diagnostic heights where the *maximum* energy, etc. transfer occurs (ReVelle, 2002a) to help guide the modeling results and to check various regimes of validity since the entire modeling

process is a numerical modeling effort and subject to various well known numerical instabilities, etc.

As noted in ReVelle (1979), we computed the small downward height step interval, Δz as a function of the instantaneous meteor velocity over sufficiently small velocity increments to preserve the constant ablation parameter solution (ReVelle, 1979). We continued with a single-body type approach until fragmentation was triggered if the stagnation pressure exceeded the specified breaking strength of the body.

We utilized sufficiently small velocity steps so that $\{(1/\sigma(z)) \cdot \partial \sigma(z)/\partial z \cdot \delta z\} \ll 1$ was maintained throughout the entry. During this evaluation process, there is a specific dependence that is related to the flow regime type (body size dependence and bulk density dependence), flight velocity, entry angle, shape, meteoroid composition, mean volume porosity, etc. and these various dependencies extend throughout all parts of the modeling simulations.

If breakup was predicted to occur, we allowed progressive fragmentation of the body after a specified time lag for transfer of fragments to the near-wake, so that splitting into an increasing number of equal size pieces could occur. This cascade is continued either the body impacts the ground (or until the final number of fragments specified has been exceeded). After the rapid wake transfer, we allowed the fragments to either always remain in the wake while continuing to ablate (non-collective wake limit) or we allowed the fragments to rapidly migrate forward in the low density air to join the main mass as a collective wake that is composed of a porous, large group of bodies also undergoing ablation as in Sepri, et al. (1981). Finally, we computed the fragmentation scale height as a function of height and of μ for the conditions at all heights below the breakup height. This allowed us to evaluate whether single-body model or a fragmentation type approach was most needed.

The overall model results, given the complexity of the unknowns of both the atmosphere and of the bolides themselves, are of sufficient quality that they should be considered as just as reasonable or in some cases even better than (in terms of all the modeled variables) other previously developed theoretical models.

3. Mechanical Wave Generation and Wave Propagation

During the penetration of a sufficiently large body into a planetary atmosphere, mechanical waves are continuously generated. This process can be captured by using the Knudsen number that was defined earlier. This new parameter is plotted in Figure 6 along with the classical Kn value. Entry conditions for this vertical entry case included an initial radius = 10^{-4} m (sphere of unchanging shape), entry velocity = 22 km/s, 50% porosity (with respect to a density of $3.70 \cdot 10^3$ kg/m³), $D=4.605$, etc.

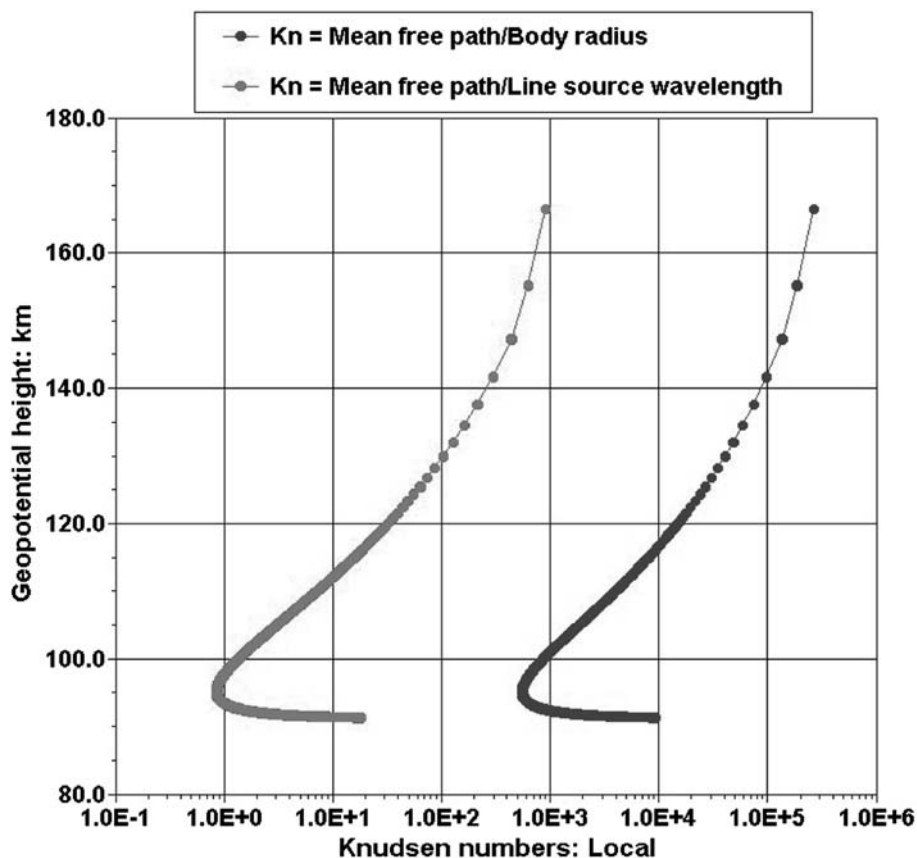


Figure 6. The modified Knudsen number and the classical Knudsen number as a function of height for very small entering meteoroids (with the classical Knudsen number $\gg$ modified Knudsen number – for details see the text).

This parameter was invented to evaluate the total power balance for small meteoroids (for which Kn is not in continuum flow, but for which Kn^* is definitely in the continuum flow regime). Utilizing Kn^* and the ε , a total power balance can be nearly achieved, even for very small meteoroids. These very diffuse, line source, high altitude blast waves are spread out over a much broader region than their counterpart at lower continuum flow heights and are a necessity if the power balance is to be satisfied at all heights for smaller meteoroids.

3.1. METEOROID WAVE SOURCE MODELS: “AIRWAVE” OBJECTS

We will analyze the infrasound and to a lesser extent, the IGW from bolides using the following conceptual blast wave source models:

- (a) Idealized line source model for an infinite velocity bolide (in the no deceleration limit): The Mach cone half angle $\equiv 0^\circ$ so that only a highly directional cylindrical radiation pattern of AGW's is envisioned. This pattern is so directional that bolides entering steeply will subsequently have much of their wave energy refracted upward.
- (b) Modified line source (due to fragmentation effects): There can be significant local ripples in the wavefront from fragmentation effects along the entry path. In the extreme gross-fragmentation limit, a protruding "omni-directional head" (for a rapidly moving point source with acoustic radiation generated in the form of quasi-spherical waves) will also lead the rearward regime of an extremely narrow type (a) line source Mach cone.
- (c) Supersonic source: Non-zero Mach cone half angle whose value depends on the local sound speed and upon the instantaneous velocity of the entering meteoroid. In this case significant deceleration has occurred and very complicated acoustic radiation and subsequent refraction patterns can result (see below).

Data generated by these bodies during hypersonic entry into the earth's atmosphere were not anticipated by monitoring networks and came to be known as "airwave" objects (ReVelle, 1997).

Finally, as discussed in ReVelle (1976, 2001d), using model (a) above, there is a *minimum* infrasonic detection threshold for bolides corresponding to a blast radius $> \sim 10$ m (Kraemer and Bartman, 1981). This corresponds to a minimum bolide panchromatic luminosity from ~ -5 to -6 or brighter in order to be detectable at ground level by an array of conventional pressure wave sensors. Expressed in terms of the bolide kinetic energy, this corresponds to values between 10^{-6} and 10^{-5} kt (or 2–20 pounds of TNT equivalent energy release).

3.2. ATMOSPHERIC AGW MODELING AND ENERGETIC PROPAGATION INVARIANTS

From the work of Golitsyn et al. (1977), in general there are four relevant atmospheric resonant frequencies even in the simplest possible atmospheric model, i.e., for an isothermal, hydrostatic atmosphere (only three of which are independent for a constant value of γ):

$$\omega_{co}^2 = \{c_s/(2H_p)\}^2 \quad (20a)$$

$$\omega_{co}^2 = \{\gamma/2/(g/c_s)\}^2 = \text{acoustic waveguide cut-off frequency squared} \quad (20b)$$

$$\omega_a^2 = g/(2H_p) = \{\gamma/2\} \cdot \{g/c_s\}^2 = \omega_{co}^2/(\gamma/2) \quad (20c)$$

$$\omega_g^2 = (\gamma - 1) \cdot (g/c_s)^2 = \text{Isothermal Brunt-Vaisalla frequency squared} \\ \text{(or the square of the internal gravity wave cut-off frequency)} \quad (21)$$

$$\omega_c^2 = \omega_g^2 \cdot \cos^2 \theta' = \text{Buoyancy launch angle frequency squared} \quad (22)$$

where θ' = internal gravity wave launch angle (relative to the horizontal); H_p = pressure scale height (as earlier defined).

These resonant frequencies define the wave regimes in two branches (with evanescent Lamb waves existing at *all* frequencies, but exclusively between ω_g and ω_{co}):

$\omega_{co} \leq \omega \leq \infty$: Acoustics/infrasonic waves; $\omega_{co} \leq \omega \leq \omega_g$: Internal gravity waves

The interested reader is referred to Mihalas and Weibull-Mihalas (1999) for an evaluation of these frequencies in hydrostatic, non-isothermal and ionized media respectively.

3.2.1. Modeling approaches for AGW's

The types of modeling approaches utilized for propagation of AGW's include "ray" or wave normal theory (geometrical acoustics), Normal mode waveguide (full wave) theory, Ray-mode theory and also numerical integration techniques, etc.

The wave normal "ray" tracing equations or Geometrical "particle" acoustics (non-dissipative limit) can be justified by using the size parameter, S , as defined in optics. If we define $S = 2\pi \cdot \{r/\lambda\}$, where r = "obstacle scale" redirecting the wave and λ = wavelength (at the maximum amplitude of the wave), then we can identify regimes as (a) $S \gg 1$, Geometrical acoustics, (b) $S \sim O(1)$: Wave diffraction regime or (c) $S \ll 1$: Wave scattering regime

Furthermore, we can also define the ray mode transition distance for a uniform waveguide, i.e., $R_{rm} = 2 \cdot H^2/\lambda$ (Cepelch et al., 1998), where H = vertical duct thickness, then compare the current range, R so that if:

- (a) $R < R_{rm}$, Geometrical acoustics is applicable (more "rays" than modes exist), whereas if
- (b) $R > R_{rm}$, Full wave theory is applicable (more modes than "rays" exist).

There are two geometric acoustics *kinematic* invariants in a horizontally stratified, steady, range-independent medium (Lindsay, 1960), namely:

- (a) Wave normal heading angle, ϕ , as defined at the source: $\phi = \text{constant}$
 (b) Characteristic velocity (the Snell's law constant), $K = \text{constant}$

For *stationary point* sources (for all possible azimuths):

$$K(z) = (c_s / \cos \theta') \quad (23)$$

θ' = wave normal launch angle with respect to the local horizontal.

For moving *line* sources:

If $V(z) \gg c_s$: Hypersonic flow

$$K(z) = (c_s / \sin \theta) \cdot \{\sin^2 \theta + (1 - 2 \cdot (\Delta\phi/\pi))^2 \cdot \cos^2 \theta\}^{1/2} \quad (24a)$$

θ = horizontal entry angle of the bolide.

For $V(z) > c_s$: Supersonic flow or for supersonically moving point sources:

$$K(z) = c_s(z) \cdot V(z) / \{|(V^2(z) - c_s^2(z))^{1/2} \cdot \sin \theta - c_s(z) \cdot \cos \theta|\} \quad (24b)$$

The above treatment neglects non-linear refraction within R_0 of the trajectory.

If steady state winds are included the term, $|V_H| \cdot \cos(\phi - \psi(z))$ must also be added to the right hand side of the various expressions for $K(z)$.

3.2.2. Wave energy conservation properties

Wave kinetic energy density conservation: (Dissipationless wave propagation)

$$\text{Kinetic energy density} \equiv 1/2 \cdot \rho(z) \cdot \{\Delta u^2(z)\} = \text{constant} \quad (25a)$$

since:

$$\Delta u(z) \equiv \Delta p(z) / \{\rho(z) \cdot c_s(z)\} \text{ for acoustic (infrasonic) waves} \quad (25b)$$

$$\Delta u(z) = \text{perturbation wind due to the wave}$$

$$\therefore 1/2 \cdot \Delta p^2(z) / \{\rho(z) \cdot c_s^2(z)\} = \text{propagation constant} \quad (25c)$$

where $\rho(z) = \rho_0 \cdot \exp(-z/H_p)$ in an isothermal, hydrostatic atmosphere for example; ρ_0 = surface air density

Thus, for upward (downward) propagation, we expect increasing (decreasing) effects of non-linearity and $\delta u(z)$ increases (decreases) exponentially while $\Delta p(z)$ decreases (increases) exponentially. Knowledge of the wave kinetic energy density at all points on the entry trajectory and of the infrasonic amplitude, Δp at the ground ($z=0$) allows a reliable calculation of the source energy (ReVelle et al., 2004). In general, the pressure wave amplitude of the propagating wave is expected to be a function of range, blast

wave radius, line source length, differential acoustic efficiency, etc (Edwards et al., 2004).

3.3. DOCUMENTED IGW'S FROM BOLIDES

The primary analytical theoretical treatment of AGW's from bolides is given by Golitsyn et al. (1977) for the far-field limit of "linearized" perturbations. A recent application of their asymptotic high frequency infrasonic technique can be found in Shumilov et al. (2003) for the Vitim bolide (see below). The application of infrasonic formulae in this case seems to be incorrect however since these observations are for the internal gravity waves from this bolide due to the very long observed periods.

The treatment in Golitsyn et al. although mathematically quite rigorous, suffers from the fact that it is not numerical or more flexible and can not be directly connected to the complex atmospheric environment through which AGW's must travel to a distant observer.

There have been a number of detections of IGW's from bolides, including Tunguska (6/30/1908), Revelstoke (3/31/1965) over Canada, possibly Kincardine (9/17/1966) over Lake Huron, other large bolides listed in ReVelle (1997), possibly the Crete bolide (6/02/2002) and finally the Vitim bolide (9/24/2002) over northwestern Siberia (Personal communication with O. Popova, Institute of Dynamics of Geospheres, Moscow). This topic has been studied very little compared to the infrasonic case, but it seems clear that the orientation of the bolide source with respect to the gravitational field of the earth is very important for IGW production. All of the above cases had rather flat entry angles with respect to the local horizon.

An analysis of the limiting cases of vertical and horizontal entry show that IGW's have their "parcel" oscillations parallel to the earth's gravitational field if the entry angle is close to being horizontal, but this is only the case for "rays" emanating at large azimuths outside of the plane of entry (nearly horizontal wave normals). For vertical entry, IGW's have their "parcel" oscillations parallel to the gravitational field. In such cases the gravitational field can provide a buoyant restoring force, thus efficiently producing IGW. Since the acoustical waves are longitudinal rather than transverse, these conclusions do not apply to them as expected.

In addition, Golitsyn et al. (1977) have also determined the differential conversion efficiency (relative to a point source) for AGW's from bolides:

$$\eta_{\text{inf}} = (\gamma - 1)^2 / \{2(2\pi)^{3/2}\} \approx 0.50\% = \text{Differential acoustic efficiency} \quad (26a)$$

$$\eta_{\text{grv}} = (\gamma - 1)/\{2(2\pi)^{3/2}\} \approx 1.0\% = \text{Differential IGW efficiency} \quad (26b)$$

with $\gamma = 1.40$ for air considered as a perfect, diatomic gas (for Earth's atmosphere).

These above values can be readily compared to those computed using our most recent detailed entry modeling techniques (ReVelle, 2001a, 2002a, 2004):

- (i) Neuschwanstein: $\sim 5.0\%$ differential “acoustic” efficiency near the end of the visible trajectory.
- (ii) Tagish Lake: $\sim 0.30\%$ differential “acoustic” efficiency near the end of the visible trajectory.
- (iii) Tunguska: $\sim 0.030\%$ differential “acoustic” efficiency near the end of the visible trajectory.

Thus, there is a definite downward trend in ε as size or mass increases. This makes good physical sense since $\varepsilon \propto \{1/R_0^2 \cdot l\}$ from our current theory.

3.4. WAVE NORMALS AND RAY PATHS: TRACING THE ATMOSPHERIC TRAJECTORIES OF INFRASONIC WAVES

The equations needed to describe the propagation paths of “linearized” AGW's in a horizontally stratified, range independent, steady state atmosphere can be written in the group velocity $\{x, y, z\}$ component form (Lindsay, 1960, ReVelle, 1976, Landau and Lifschitz, 1987):

$$c_{gx}(z) = dx/dt = c_s(z) \cdot \{\alpha \cdot \sin \phi - \beta \cdot \cos \phi\} + u(z) + d\phi/dt \cdot y \quad (27a)$$

$$c_{gy}(z) = dy/dt = c_s(z) \cdot \{\alpha \cdot \cos \phi + \beta \cdot \sin \phi\} + v(z) - d\phi/dt \cdot x \quad (27b)$$

$$c_{gz}(z) = dz/dt = \pm c_s(z) \cdot \gamma + w(z) \quad (27c)$$

where $c_s^2 = \{\gamma \cdot p/\rho\}$; $c_s = f \cdot \lambda$; f = wave frequency; λ = wavelength; c_s = adiabatic thermodynamic phase velocity; $\{u, v, w\}$ = zonal, meridional and vertical wind components (time- and space-averaged values).

Equations (27a–27c) have direction cosines: $\alpha = \cos \theta$; $\gamma = \sin \theta$; $\alpha^2 + \beta^2 + \gamma^2 = 1$ so that $\beta = 0$ for a plane wave system. In this system of equations, locally plane waves were assumed with the wave propagation

angle θ measured upward from the local horizontal and where ϕ = wave normal heading angle (measured clockwise from geographic North).

Throughout this description we are implicitly ignoring non-linear refractive effects due to the fact the energy deposition process modifies the medium locally so that the sound speed experiences a gradient along the wavefront with progressively lower temperatures farther away from the entry trajectory. This non-linear refraction occurs primarily within one blast wave relaxation radius of the trajectory ($x = 1$, where $x = R/R_0$) whereas all subsequent wave normal path tracing will be done for $x > 10$.

Strictly speaking, the $d\phi/dt$ terms above are all zero in a range independent medium, but we have included them for completeness. We have also included β terms for non-plane waves. Integration of these equations in a specified medium allows the resulting wave normal paths to be identified. The paths of these “wave normals” (not the corresponding “rays”) are Galilean invariant and are the proper quantities to be evaluated (Hayes, 1971). Note that in a windless medium the ray and wave normal definitions are totally equivalent.

The wave normal paths can be readily identified if we assume an instantaneous source (so that a matching of the wavefront phase with its source altitude can be made) and the type of explosion event, i.e., a moving point versus a line source form of $K(z)$, etc. The basic difference between the two extreme limits of the characteristic velocity is that the infinite speed line sources are very directional unlike the stationary point source problem in which all “ray” launch directions are possible.

As discussed in Revelle (1976, 1997), the launched wave normals must satisfy the waveguide conditions in order for long distance ducting of the signal to occur, i.e., $K > c_{\text{eff}}(z=0)$ between the ground and various layers aloft in the Earth’s atmosphere (Ceplecha et al., 1998). Examples of wave normal paths in three different planes, namely $\{x,z\}$, $\{y,z\}$ and $\{x,y\}$ are given in detail for the Neuschwanstein bolide in ReVelle et al. (2004).

4. Summary and Conclusions

A theoretical entry model that includes the shape change parameter, μ , that encompasses all major physical processes during entry has been developed and applied to a large range of meteoroid types and sizes. The model was developed utilizing an energetics analysis that successfully predicts the end height after a fixed percentage of the original kinetic energy has been exceeded. This approach was shown herein to be equivalent mathematically to the classical end height of ReVelle (1979). The treatment explicitly allows for either a homogeneous or a porous meteoroid and for either a single-body or a fragmentation cascade model (only triggered if the stagnation pressure on the

frontal cross-section exceeded the breaking strength of the meteoroids). Fragments were transferred to the near-wake where they were either allowed to interact with the main leading body (collective wake model) or remained in the wake as they ablated away with time (non-collective wake model). An intermittent mode which invoked both of these limits is also being actively studied. Bolide luminosity was also computed for all cases using the recently developed, panchromatic luminous efficiency of ReVelle and Cepplecha (2001f, 2002). Available bolide luminosity outputs were properly calibrated in terms of either panchromatic stellar magnitude or in terms of Watts/steradian (applicable at 100 km in the zenith).

Also, we performed a normalized panchromatic total power balance using the various differential efficiencies. We also developed a “first principles” form of the differential acoustical efficiency which was allowed to evolve independently of all of the other types which were functionally related to the panchromatic differential luminous efficiency. This approach has been applied to a number of cases including Neuschwanstein (ReVelle et al., 2004), etc. Finally, we compared these predictions to Golitsyn et al. (1977) and found some similarities, but also many differences.

Finally the topic of the spectrum of atmospheric AGW's has been presented in order to assess how this new channel of information, i.e., IGW's, can be used to assess bolide source properties. In addition the acoustical wave normal group velocity equations were presented for a horizontally stratified steady state range-independent atmosphere to study the complex refraction effects associated with bolide infrasound generation and ground-based detection. We have also summarized the energetic constraints during acoustic/infrasonic wave propagation that have also been successfully used to evaluate the Neuschwanstein meteorite fall (ReVelle et al., 2004).

There is much more future work yet to be done. This includes many more details on the fragmentation and related processes, high altitude transitional Knudsen number *interference* heating effects, precursor ionization/free stream absorption modeling, i.e., the radar head echo problem, temperature calculations for realistic conditions, etc. The latter calculations, for example, have already been formally carried out for the case of the leading shock front for the case of equilibrium, chemically reacting air using standard hypersonic aerodynamic methods, but there was not sufficient space to elaborate on this topic in this brief review.

Appendix A: Energetics End Height Single-body Equation Equivalence

$$z_{KE}(V) = -H_p \cdot \{\ln(p_\infty^*/p_0) \cdot \exp[-(\sigma \cdot F) \cdot V_\infty^2] \cdot \{D - D'\} + \exp[-z'/H_p]\} \quad (\text{A.1})$$

$$z' = -H_p \cdot \{\ln(p_\infty^*/p_0) \cdot (2gH_p/V_\infty^2)\} \quad (\text{A.2})$$

$$D' = -\{Ei[(\sigma \cdot F) \cdot V_\infty^2] - Ei[(\sigma \cdot F) \cdot V^2(z)] - \ln(V_\infty/V(z))^2 - [(\sigma/2)(V_\infty^2 - V^2(z))]\} \quad (\text{A.3})$$

where $Ei(\sigma \cdot F)$ = the exponential integral function; $F = (1 - \mu)/2$; $-2(*) \leq \mu \leq \sim 1$; $\mu = 2/3$ is the self-similar value (no shape change); $p_\infty^* = \text{mg} \cdot \sin \theta / (C_D A)$ = modified ballistic entry parameter; $p_\infty^* = 4 \cdot \rho_m \cdot r \cdot g \cdot \sin \theta / (3C_D)$ for a sphere; p_0 = surface pressure; $D = 4.605$ for 99 % kinetic energy depletion at the end height.

(*) : *Effective “pancake” model limits for $\mu < 0$*

Starting from the classical (geopotential) end height equation using standard notation as given in ReVelle (1979, 1980, 1987) written assuming $\mu = 2/3$ so that $F = (1 - \mu)/2 = 1/6$ for simplicity with $\sigma = \text{constant}$, i.e., the so-called simple ablation theory:

$$z(V) = -H_p \cdot \ln\{\exp(-z'/H_p) + 2(p_\infty^*/p_0) \cdot \exp[-\sigma V_\infty^2/6] \cdot (\Delta Ei/2)\} \quad (\text{A.4})$$

$$\text{KE}(z) = \text{KE}_\infty \cdot \exp[-D] \quad (\text{A.5})$$

$$M(z) = M_\infty \cdot \exp[-(\sigma/2) \cdot \{V_\infty^2 - V^2(z)\}] \quad (\text{A.6})$$

where

$$\Delta Ei \equiv Ei(\sigma V_\infty^2/6) - Ei(\sigma \cdot V(z)^2/6)$$

$$\text{KE} = 1/2 m \cdot V^2; \text{KE} = 1/2 m_\infty \cdot V_\infty^2; D = \alpha + \beta \text{ (ReVelle, 1980)}$$

As shown in ReVelle (1980), ΔEi can be expanded in an infinite length power series form that can also be expressed as the difference between two very simple functions in (A.9):

$$\Delta Ei = \ln(\{\sigma V_\infty^2/6\}/\{\sigma V^2(z)/6\}) + \Delta = \ln(V_\infty^2/V^2(z)) + \Delta \quad (\text{A.7})(\text{A.7})$$

$$\begin{aligned} \Delta = & (\sigma/6) \cdot (V_\infty^2 - V^2(z)) + (1/4) \cdot (\sigma/6)^2 \cdot (V_\infty^4 - V^4(z)) \\ & + (1/18) \cdot (\sigma/6)^3 \cdot (V_\infty^6 - V^6(z)) + \dots \end{aligned} \quad (\text{A.8})$$

$$\Delta = \Delta Ei - \ln(V_\infty^2/V^2(z)) \quad (\text{A.9})$$

Also, from (A.5) and (A.6) we can write:

$$V(z) = V_\infty (M_\infty/M(z))^{1/2} \cdot \exp[-D/2] \quad (\text{A.10})$$

$$(M_\infty/M(z))^{1/2} = \exp[(\sigma/4) \cdot (V_\infty^2 - V^2(z))] \quad (\text{A.11})$$

Combining these two expressions in (A.10) and (A.11), we can also write:

$$\ln(V(z)/V_\infty) = (\sigma/4) \cdot (V_\infty^2 - V^2(z)) - D/2 \quad (\text{A.12})$$

Rearranging (A.4) into a form solved for the velocity and as the natural logarithm of the velocity as a function of z , we also have:

$$V(z) = V_\infty \cdot \exp\{-[p_0/(2 \cdot p_\infty^*)] \cdot \exp[\sigma \cdot V_\infty^2/6] \cdot (\exp(-z/H_p) - \exp(-z'/H_p) - \Delta/2)\} \quad (\text{A.13})$$

$$\ln(V(z)/V_\infty) = -[p_0/(2 \cdot p_\infty^*) \cdot \exp[\sigma \cdot V_\infty^2/6] \cdot (\exp(-z/H_p) - \exp(-z'/H_p) - \Delta/2)] \quad (\text{A.14})$$

Equating (A.12) and (A.14), we can solve again for $z(V)$ in the form:

$$z(V) = -H_p \cdot \{\ln[\{p_\infty^*/p_0\} \cdot \exp[-\sigma V_\infty^2/6] \cdot \{D - (\sigma/2) \cdot (V_\infty^2 - V^2(z)) + \Delta\} + \exp(-z'/H_p)]\} \quad (\text{A.15})$$

Defining:

$$D' \equiv (\sigma/2) \cdot (V_\infty^2 - V^2(z)) - \Delta \quad (\text{A.16})$$

$$z(V) = -H_p \cdot \ln[\{p_\infty^*/p_0\} \cdot \exp[-\sigma V_\infty^2/6] \cdot \{D - D'\} + \exp(-z'/H_p)] \quad (\text{A.17})$$

where

$$D' = -\{\Delta Ei - \ln(V_\infty/V(z))^2 - (\sigma/2) \cdot (V_\infty^2 - V^2(z))\} \quad (\text{A.18})$$

Equation (A.17) and (A.18) are the desired results. Thus the classical end height equation has been shown to be totally equivalent to the energetics approach used throughout this paper written in terms of the D parameter of

ReVelle. The solutions that we have used to make predictions use the variable ablation parameter form of these equations developed in ReVelle (1979). Thus, all solutions are numerical results in thin vertical layers over small velocity change intervals rather than the simple analytic results developed above.

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FRAGMENTATION MODEL ANALYSIS OF EN270200 FIREBALL

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Abstract. We present results on the MFM analysis (Meteor fragmentation model recently proposed by Cep-lecha and ReVelle, 2005) of EN270200, a type-I fireball of maximum absolute magnitude -10 from February 27, 2000, 19 h 22 m 57 s UT, based on observational data from four Czech stations of the European Fireball Network equipped with fish-eye cameras. Radiometer record of the light curve with time resolution of 1200 records per second is also available. Two grating spectra point to composition of an ordinary chondrite. Data on height and stellar magnitude were available at 73 individual trajectory points. The standard deviation of our fit was ± 28 m for height as function of time and ± 0.11 magnitude for the light curve. Ablation coefficient was found to be constant during the entire trajectory ($0.004 \text{ s}^2 \text{ km}^{-2}$). The shape-density coefficient varied in a wide range of values (1.65 and 0.12 c.g.s.). We found 17 fragmentation events during the entire photographic light curve, 7 of them larger than 1% of the main body mass. All fragmentation occurred in a form of clusters of tiny fragments. The initial mass resulted as 3.6 ± 0.2 kg at a height of 80.144 km with velocity of 18.790 km s^{-1} , and the terminal mass was 0.27 ± 0.02 kg at a height of 31.62 km with velocity of $6.64 \pm 0.12 \text{ km s}^{-1}$. We were able to explain the very short millisecond flare by the MFM model.

Keywords: Ablation, fireball, fragmentation, light curve, photographic observation

1. Observational data

EN270200 is a type-I bolide of maximum absolute magnitude -10 from February 27, 2000, at 19 h 22 m 57 s UT. Data from four Czech stations of the European Fireball Network equipped with fish-eye cameras are available. Ondřejov data include also photometric data with a very high time resolution of 1/1200 second obtained from a radiometer (Spurný et al., 2001). Additionally, two grating spectral records with some 200 lines in visible pass band are also available. The line intensities of Na, Mg, Cr, Mn, Fe, and Ni are very similar to the EN151068 fireball spectrum (Borovicka, 1993) and correspond to a chondritic composition. Time marks (breaks) on zero-order images of the spectral records were also used for measurement and computation of distances along trajectory and heights, and yielded better precision than the fish-eye records because of longer focal distance of the spectral cameras. The luminous atmospheric trajectory was determined from all available photographic records with very high precision (Figure 1). Data on

height, distance along the trajectory, and stellar magnitude are available at 73 individual points of the trajectory defined on the photographic records by rotating shutter time marks. Time and distance along the trajectory are relative values; thus we have chosen as a zero point (from where the integration starts) a height somewhat above the observed beginning point, i.e. $t = 0$ and $l = 0$ was set at $h = 85.000$ km. The resulting observational input data comprise combined values on time, height, distance along the trajectory and absolute magnitudes derived from the Ondřejov fish-eye camera and from the better of both zero-order spectral images. Several time marks at the early parts of the trajectory were not well defined and were thus measured only a rough way for the purpose of defining height for the brightness measurements: these points were used only for the light curve and *were not used* for the dynamic solutions (i.e. for solutions of $h = h(t)$). Comparison of photographic and radiometric light curves is presented in Figure 2. The fit is reasonably good and at least part of the differences may be caused by differences in spectral sensitivity of both systems.

We will not study these differences in this paper. However, there is a wealth of information hidden in due to existing spectral records, and we will present a thorough study of these differences in close future. We did not use most of the radiometric data in this analysis because of unknown luminous efficiencies of the radiometer pass band. Radiometer spectral sensitivity has its maximum at substantially larger wavelengths than the photographic panchromatic emulsion implemented (Spurný et al., 2001). Panchromatic luminous efficiency is rather well known and mostly calibrated by MFM

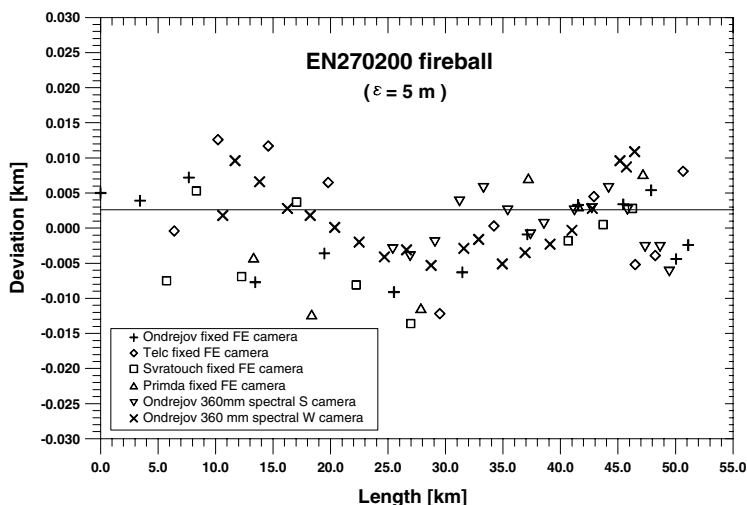


Figure 1. Deviations of lines of sight of individual measured points from the average trajectory for all available images. Y-axis is highly enlarged. ϵ is a standard deviation of one measured point from the least square fit of the average trajectory.

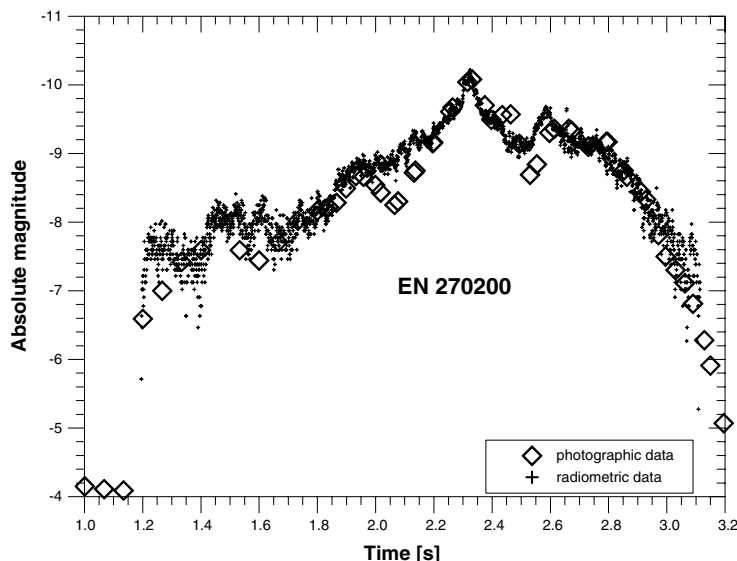


Figure 2. Comparison of the photographic and radiometric light-curves of EN270200 fireball.

analysis of the Lost City dynamic and photometric data (panchromatic emulsion used), and with the masses of recovered meteorites (Ceplecha and ReVelle, 2005). However, we were interested, if the MFM model could explain a very short flare of 0.0034 s duration observed by radiometer at $t = 2.655$ s. Such short flares cannot be observed photographically due to smearing effect of the moving source, while radiometer can follow them easily due to instant recording each 1/1200 s. Thus we added just this very short flare to the photographic data. The flare can be seen in enlarged part of Figure 3, where the observed light-curve and its MFM fit are presented.

As can be seen in Figure 1 precision of the geometrical position of the trajectory is better than ± 10 m, which is partly due to a very small distances of the body from the cameras. The EN270200 bolide was closer to the Ondřejov camera than 81 km throughout the entire trajectory; the terminal point was the closest being only 46 km from the Ondřejov camera. Basic data on the atmospheric trajectory, radiant and heliocentric orbit were already published by Spurný et al., 2001.

1.1. EXPLANATIONS AND DEFINITIONS

The term Gross-Fragmentation Model (GFM) we use for procedures described in Ceplecha et al. (1993). They are based entirely on dynamical behavior. The GFM *fits* observed values of height and distance along trajectory, both as function of time. However, the GFM *does not fit* the light-

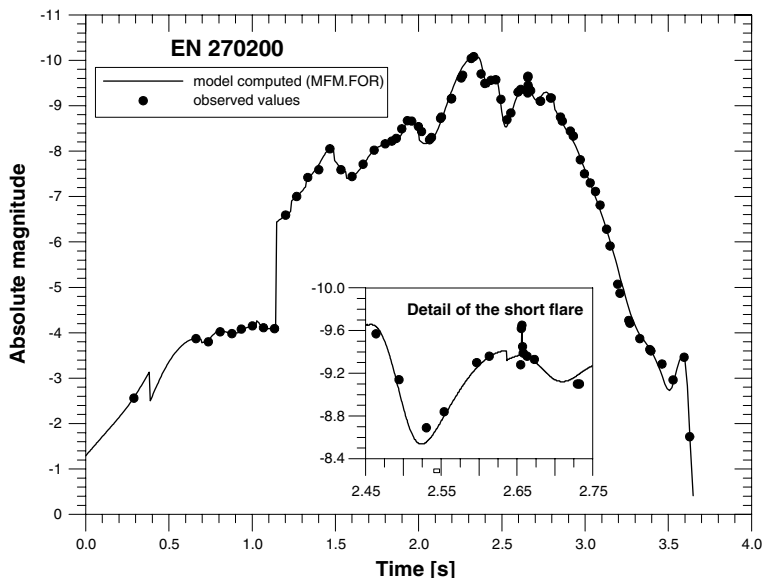


Figure 3. Light-curve of the EN270200 fireball – Fit of the observed data with MFM model and detail of the millisecond flare recorded by radiometer.

curve. The procedure is capable in finding only one fragmentation point (height) inside a given interval and does not involve data on meteor brightness (light-curve). The same value of ablation coefficient is assumed before and after the fragmentation point.

The term Meteoroid Fragmentation Model (MFM) we use for procedures which will be published soon (January 2005) in MAPS (Ceplecha and ReVelle, 2005). This model fits both the light-curve and height as function of time (height-curve). It involves any number of fragmentation points and two types of fragmentation: (1) into large pieces comparable to the main body in size, (2) into a cluster of very small fragments. The ablation coefficient and the shape-density coefficient are allowed to be variable with height/time. Luminous efficiency is assumed to be variable with velocity, mass and height (calibrations were performed mostly by MFM solutions for the Lost City fireball and by masses of its recovered meteorites). Two limiting assumptions are inevitably demanded in the MFM: (1) the main body is the leading one throughout the entire trajectory, (2) the luminous efficiency of the main body and of its fragments are identical. The MFM completely explains the differences of dynamically and photometrically determined masses, a puzzle in meteor science for many decades.

The apparent values of the ablation coefficient, σ , and apparent values of the luminous efficiency, τ , are those computed from observational (dynamic and photometric) data of the main body neglecting the fragmentation process.

The intrinsic values of σ and τ are those computed from observational (dynamic and photometric) data of the main body including the fragmentation process.

The intrinsic values of σ and τ are the apparent values corrected for the effect of fragmentation.

1.2. GROSS-FRAGMENTATION MODEL

The GFM (Ceplecha et al., 1993) yielded only a single-body solution with

$$\text{apparent } \sigma = 0.0177 \pm 0.0005 \text{ s}^2 \text{ km}^{-2}$$

$$m_1 = 0.439 \pm 0.007 \text{ kg}$$

$$\varepsilon_h = \pm 0.029 \text{ km}$$

$$m_E = 0.030 \pm 0.002 \text{ kg}$$

$$v_1 = 18.813 \pm 0.007 \text{ km s}^{-1}$$

ε_h is standard deviation for one measured height

If one fragmentation point is assumed, both solutions (realistic and unrealistic) are very close to each other and also close to the single-body solution. All these solutions are within one standard deviation limits (actually very close to the limit, i.e. on the border line of standard deviations). The reason for this exceptional behavior may lie in quasi-periodic changes of K as later revealed by the MFM analysis. The light-curve computed for these parameters without fragmentation (i.e. for the single-body solution) resulted significantly fainter than the observed one. The systematic shift of the light-curve is +3.3 magnitudes and the residuals are strongly time-dependent. This is evidence that the single-body solution cannot explain the motion and radiation of EN270200 fireball.

1.3. APPLICATION OF THE METEOR FRAGMENTATION MODEL TO EN270200 DATA

MFM will be published soon (Ceplecha and ReVelle, 2005). Here we present results of application of the MFM to this remarkable EN270200 fireball. With the following values we were able to fully explain height as function of time (height-curve) and light-curve of the EN270200 fireball.

$$\text{Intrinsic } \sigma = 0.004 \pm 0.001 \text{ s}^2 \text{ km}^{-2}$$

$$\varepsilon_h = \pm 0.028 \text{ km}; \varepsilon_h \text{ is standard deviation for one measured height}$$

$K = 0.12 - 1.65 \text{ c.g.s.}$; intrinsic K is a function of time: see its values in Table I

$$h_B = 80.144 \text{ km}; \text{ we started integration at } h_1 = 85.0000 \text{ with } v_1 = 18.793 \text{ km s}^{-1}$$

$$v_B = 18.790 \pm 0.0012 \text{ km s}^{-1}$$

$$h_E = 31.62 \text{ km}$$

$$z_B = 26.9625^\circ \pm 0.0080^\circ$$

$$v_E = 6.64 \pm 0.12 \text{ km s}^{-1}$$

$$m_B = 3.6 \pm 0.2 \text{ kg}$$

$$m_E = 0.27 \pm 0.02 \text{ kg}$$

$$\varepsilon_m = \pm 0.11 \text{ magnitudes}$$

ε_m is standard deviation for one measured brightness in stellar magnitudes

Some of these results are plotted in the following Figures 4–7, where time-dependence of mass loss, deceleration and comparison of intrinsic and recomputed apparent values of ablation coefficient and luminous efficiency are presented. The resulting intrinsic K is presented in Table I together with the height and amount of fragmentation: h_f is the height of the fragmentation point (beginning of the flare) or the height where K changes, Δm is mass loss at this height in a form of fragments expressed in percent of the main body, dt_f is duration of the flare, and dt_u is the time of increasing brightness.

The standard deviation of our fit is $\pm 28 \text{ m}$ for height as function of time and ± 0.11 magnitude for the light-curve. Both residuals of height and of magnitudes are random and not dependent on time. Ablation intrinsic coefficient of $0.004 \text{ s}^2 \text{ km}^{-2}$ was found to be constant during the entire trajectory. This is a significantly lower value than the average-apparent type-I

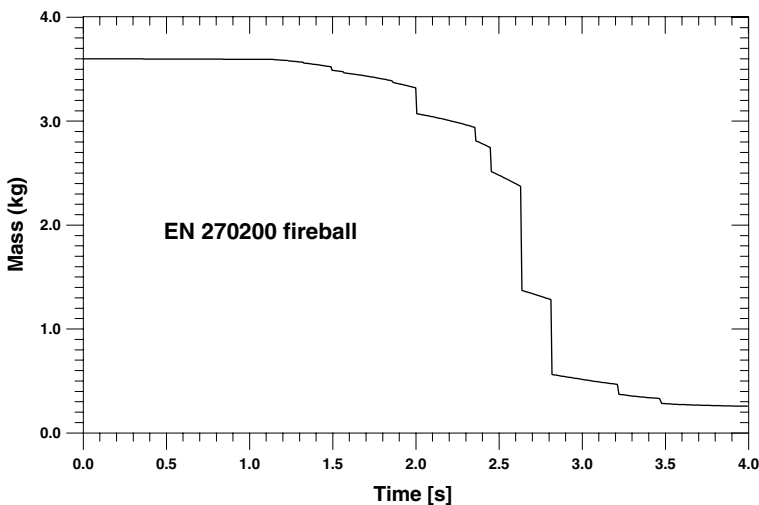


Figure 4. Time-dependence of mass loss of the main body for EN270200 fireball from MFM model.

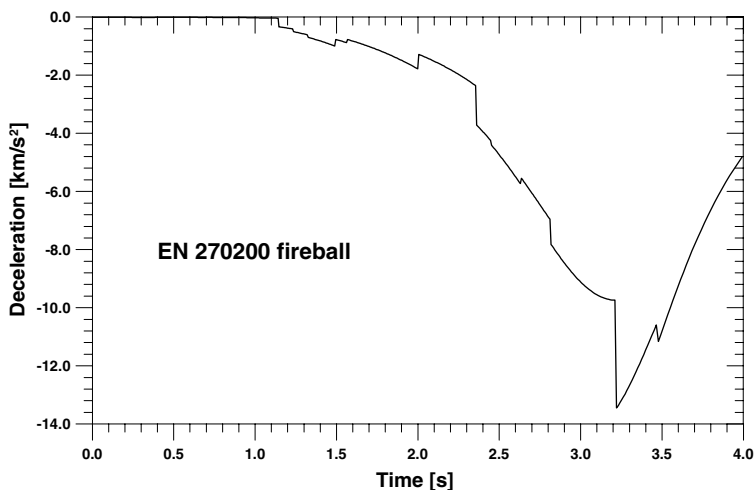


Figure 5. Time-dependence of deceleration of the main body for EN270200 fireball from MFM model.

value of $0.014 \text{ s}^2 \text{ km}^{-2}$ (Figure 6). The shape-density coefficient varied in a wide range of values between 1.65 and 0.12 c.g.s. We found altogether 18 fragmentation events during the entire photographic light curve, 7 of them were significant with mass loss larger than 1% of the main body mass. All fragmentation occurred in a form of clusters of tiny fragments. The resulting initial mass of 3.6 kg is about 8 times larger than the single-body solution. Also the terminal mass is about 8 times larger than the single-body solution.

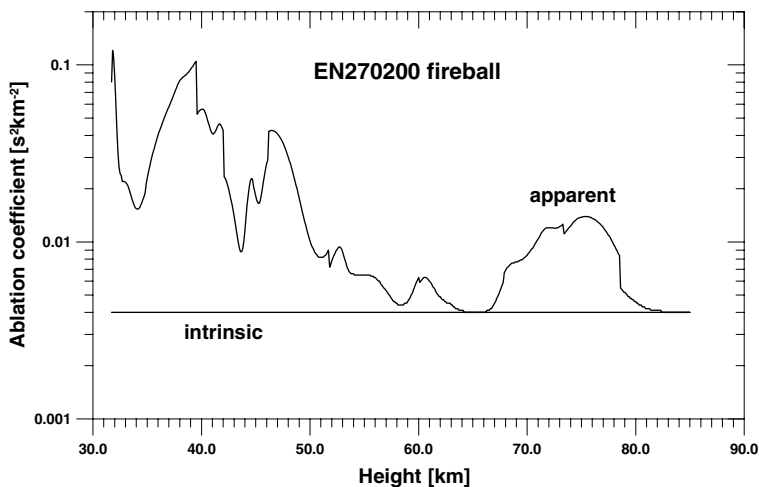


Figure 6. Comparison of intrinsic (MFM) and recomputed apparent ablation coefficients (no fragmentation) for the EN270200 fireball.

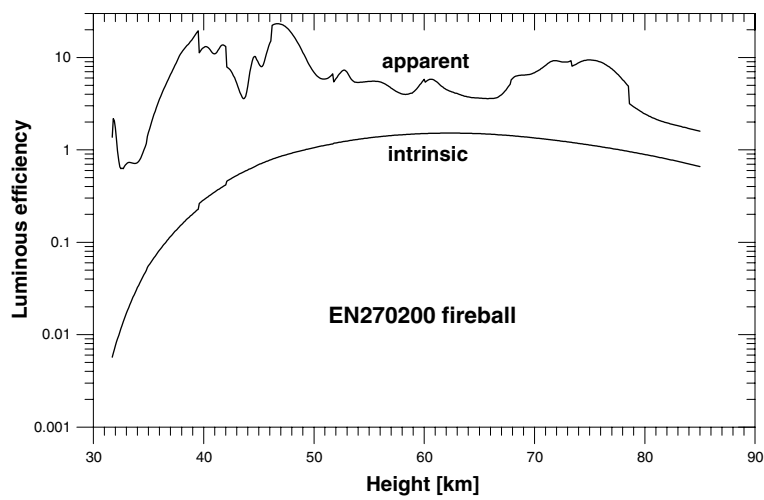


Figure 7. Comparison of intrinsic (MFM) and recomputed apparent luminous efficiencies (no fragmentation) for the EN270200 fireball.

Table I
Fragmentation history of the EN270200 fireball

t_f	h_f	Δm	dt_f	dt_u	K
(s)	(km)	(%)	(s)	(s)	(c.g.s)
0.006	84.9	0.025	1.20	0.60	0.42
0.388	78.5	0.015	0.90	0.45	0.15
0.597	75.0	0.002	0.40	0.20	0.15
0.699	73.3	0.009	0.60	0.30	0.12
1.027	67.8				0.15
1.147	65.8	0.05	0.58	0.22	1.20
1.237	64.3	0.09	0.60	0.22	1.46
1.327	62.8	0.19	0.42	0.14	1.65
1.495	60.0	0.90	1.00	0.50	1.25
1.568	58.8	0.28	0.66	0.18	1.08
1.862	54.0	0.43	0.30	0.08	1.08
2.005	51.7	7.4	0.57	0.35	0.75
2.361	46.1	4.3	0.25	0.10	1.15
2.453	44.7	8.2	0.40	0.20	1.15
2.637	42.0	42	0.70	0.14	0.92
2.655	41.74	0.05	0.0034	0.0015	0.92
2.818	39.5	56	1.00	0.14	0.78
3.221	34.8	20	0.85	0.20	1.00
3.478	32.6	14	0.22	0.12	1.02

This is evidently caused by assumption of a constant coefficient $K = 0.46$ c.g.s. in both single-body and gross-fragmentation solutions (corresponding to type-I bolide), while the MFM value of intrinsic K is larger on an average (up to 1.65) with quasi-periodic fluctuations. The main fragmentation events well correspond to directly observed fragmentation points on the zero-order image from long-focus spectral camera ($f = 360$ mm compared to $f = 30$ mm of the fish-eye camera). Two main fragmentation events were identified at altitudes of 61 and 42 km very close to the independently derived fragmentation events in Table I at heights of 60 and 42 km. This gives us a direct evidence of high altitude fragmentation under very low dynamic pressures, which were 0.09 MPa and 0.8 MPa, respectively. “Recomputed apparent ablation coefficient and apparent luminous efficiency are behaving the same way as function of time” noted one of our reviewers (see Figures 6 and 7). This evidently resulted from the fragmentation process not accounted for in apparent values: simply, the apparent values of σ and τ have no other meaning than being values derived from intrinsic values on assumption the body did not fragment, while fragmentation was the main decisive mass loss process for EN270200. Fragmentation process cannot be modeled by single-body or GFM simply assuming large values of the apparent ablation coefficient and of the apparent luminous efficiency.

2. Conclusions

The single-body solution cannot explain the motion and radiation of EN270200 fireball. On the other hand, Meteor Fragmentation Model fits the height as function of time and the light-curve with precision of the observations and can completely explain all observed data. The meaning of this statement: residuals of height as function of time and residuals of brightness as function of time are approximately the same as residuals of the observed values and moreover these two independent sets of residuals do not show any systematic trend with time (see Figures 8 and 9). No fragmentation into large pieces was necessary for explanation of the light- and height-curves.

The very short flare at $t = 2.655$ s ($h = 41.74$ km) can be easily explained by the MFM model with only 0.05% of the main body mass released (0.7 g). This has a negligible effect on the motion of the main body. The real physical reason for such an efficient process is not quite clear. However, spectral record of this extremely short flare is available and we intend to delineate the physical processes involved. Such very short and intensive flares are very

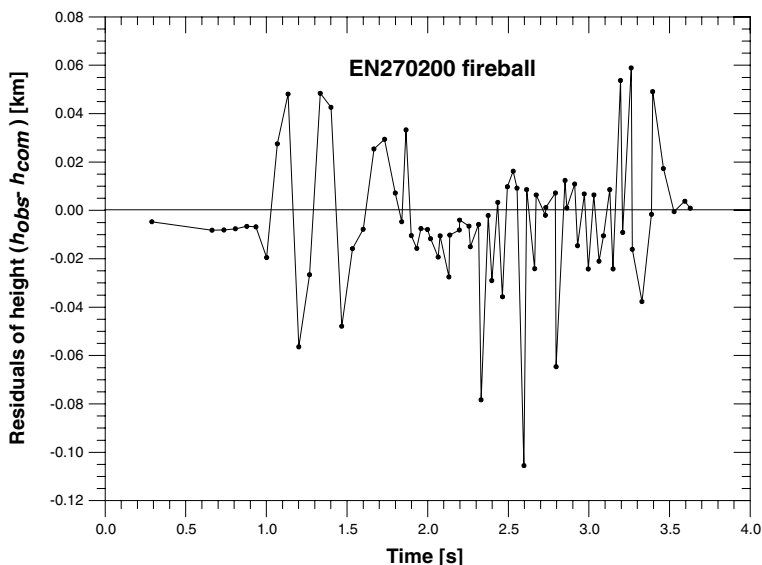


Figure 8. Residuals of the height fit. The standard deviation of this fit is ± 28 m.

typical for the radiometric records and form a recently revealed and not well-understood part of meteoric phenomena. It deserves some simple term instead of “very short flare”, perhaps “spike”?

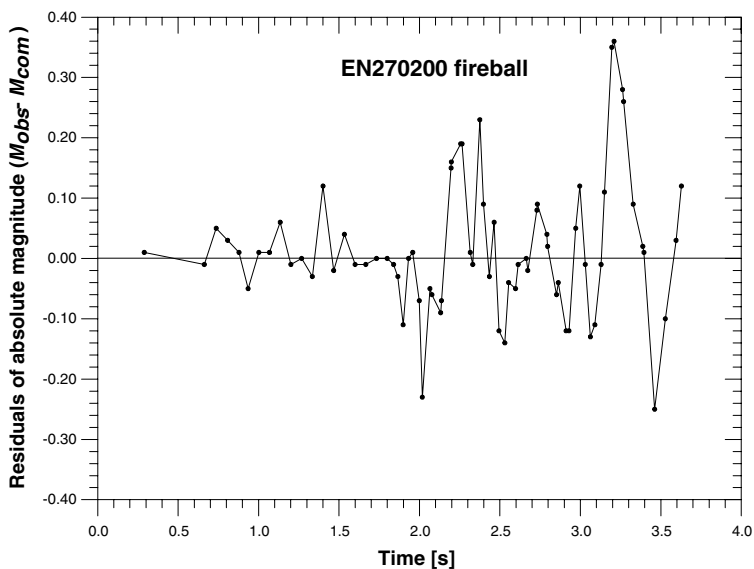


Figure 9. Residuals of the light-curve fit. The standard deviation of this fit is ± 0.11 magnitude.

Acknowledgements

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A NEW ANALYSIS OF FIREBALL DATA FROM THE METEORITE OBSERVATION AND RECOVERY PROJECT (MORP)

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Abstract. Sixty fireball cameras operated in Western Canada from 1971 to 1985. Over one thousand (1016) fireballs were recorded at more than one station, but only 367 were reduced, of which 285 have been published, including that of the Innisfree meteorite. Digitization of all the data is underway, and procedures are being developed which will allow the automatic reduction of events not previously examined. The results of the analysis of 80 fireballs reduced but not previously published are presented. When the new analysis is complete, the MORP archive will be a valuable source of information on meteoroid orbits.

Keywords: Meteors, photographic

1. Introduction

Bright meteors represent an undersampled population of solar system objects. Too small to be seen by most optical surveys of asteroids, they collide with Earth's atmosphere infrequently enough to be difficult to survey systematically. Objects in this mass range can be cometary or asteroidal, and the relative proportions of each population are not well known. There has long been an interest in streams of material which might periodically drop meteorites on the Earth, and several streams of material have been identified (Halliday et al., 1990; Drummond, 1991).

The Meteorite Observation and Recovery Project (MORP) operated a fireball network between 1971 and 1985 in Western Canada, funded by the National Research Council of Canada. The purpose of the program was to detect bright meteors which might have dropped meteorites, in order to link recovered material with its pre-collision orbit. The project did recover one meteorite, Innisfree (Halliday et al., 1978), and identified many other potential falls, though no material has been recovered from those falls to date. A flux study of large material (10^{-3} kg to 10 kg) was also conducted, using 213 analyzed records. Details of all published orbits can be found in Halliday et al. (1996) (259 orbits) and Halliday (1988) (Geminid orbits). Many dozens of fireballs which were reduced were not published, as they were not deemed likely sources of meteorites and were not selected for the flux survey.

The smaller size of the unpublished objects does not detract from their interest. It is difficult to obtain large sample sizes for bright meteors, due to the infrequency of their occurrence; the MORP archive contains data invaluable to studies of the orbits, density and characteristics of meteoroids too small to drop meteorites, but occurring too infrequently to be examined in surveys of shorter duration. The MORP data is also of interest to allow comparisons and correlations with the lunar impact data; the seismic detectors on the moon ran concurrently with the MORP survey (Latham et al., 1973). This work presents the orbits of those objects observed by MORP cameras for which analysis has been done, which have not previously been published. The digitization of all of the MORP records is currently underway, and procedures are being developed which will allow the reduction of all remaining events.

2. Observing Equipment

The MORP camera system is described in detail by Halliday et al. (1978). It consisted of 60 cameras at 12 different stations covering southern Alberta, Saskatchewan and Manitoba. The five cameras at each station were pointed 72° apart, and covered nearly the whole sky, with the exception of the area directly overhead and some gaps toward the horizon.

Each camera's field of view was 50° wide at the base, which was within 5° of the horizon. A photomultiplier mounted on each station recorded the times of very bright fireballs. Exposures between 10 and 180 min were taken on 70-mm film; the film was advanced when the cumulative sky brightness reached a certain threshold or when a bright fireball was detected. The begin and end times for each frame were recorded, but it was not always possible to determine the exact time of occurrence for a meteor. This leads to some uncertainty in determined orbits; in cases of uncertainty, the center of the exposure was selected as the time, and the uncertainty is half the length of the exposure. Each meteor presented here was recorded on at least two cameras at separate stations, allowing orbital calculations.

3. Orbit Calculations

The original trajectory data from each of the 82 unpublished meteors was used to recalculate orbits. The original measurements have been lost, so it was not possible to check all stages of the calculation, but the time, geographical location, radiant coordinates and velocity were available and sufficient for orbital calculations. In two cases, errors exist either in the recorded velocities and positions, or errors in the orbit calculations, since the

new orbits calculated differed significantly from the original analysis. These two events have been omitted from the current study, and will be published when the positions have been remeasured.

The new analysis gives the coordinates in J2000. Other than the two orbits mentioned above, differences in the original calculations and the new analysis were less than 10% in all cases, and less than 2% for most of the sample. The differences were highest on the inclinations: the average error in this was 4.2%. The large percentage errors here are confined to the low inclination orbits (less than 10°): here a small difference in the radiant position produces a relatively large percent change in inclination; the median error in inclinations less than 10° was 2.7%, compared to a median of 0.35% for inclinations greater than 10° . Differences in aphelion distance were next, with an average difference of 2.5%; the average difference in semimajor axis was 1.4%. Eccentricity and perihelion distance both had average differences of 0.6%, and the difference in ascending node was less than 0.05%. These differences are likely due to rounding differences in the original data used and the published measurements, and different Earth orbit positions in the two orbit calculations.

Calibration procedures are now being developed which will allow the quick and accurate measurement of meteors on each scanned negative from the MORP archive. When this stage is complete, over 600 additional fireball orbits will be available for analysis.

4. Results

The 80 previously unpublished orbits are listed in Tables I and II. The table lists the identifying event number, the date and time (with uncertainty in time given in minutes), the right ascension (α) and declination (δ) of the radiant, the pre-atmospheric velocity (v_∞), the beginning and end heights (h_b and h_e), and the geocentric and heliocentric speeds (v_g and v_h). The orbital elements given are the semi-major axis (a), the eccentricity (e), the perihelion and aphelion distances (q_{per} and Q_{ap}), the argument of perihelion (ω), the longitude of the ascending node (Ω), and the inclination (i). The jovian Tisserand parameter was calculated for each orbit, and the most likely source of the meteor is given. In the table, aster denotes asteroidal ($T_j > 3$), JF stands for Jupiter-family comets ($2 < T_j < 3$), and HT represents Halley-type comets ($T_j < 2$). The relative proportions of the three populations are shown in Figure 1. It should be noted that these orbits do not represent an unbiased sample of meteors in this mass range: in some cases, the meteors presented here were reduced because they looked likely to produce meteorites, but were found on analysis to have terminal masses which were too small. This sample is therefore expected to have an excess of asteroidal meteoroids, while the MORP meteors for

TABLE I
Data on MORP fireballs. See text for details

MORP number	Year	Month	Day	Time	Δt (min)	α (deg)	δ (deg)	v_∞ (km/s)	h_b (km)	h_e (km)
5	1971	2	18	4:38:43	46	145.342	11.2463	20.8	78.2	32.9
51	1971	12	21	2:23:00	1	113.927	13.2326	42.1	78	43.5
84	1976	2	4	12:06:10	0	149.62	4.7085	35	91.9	56.5
127	1974	9	3	5:45:29	0	338.997	-23.3982	18.1	79.3	35.9
148	1974	11	23	7:49:34	24	48.9654	18.98	15.7	70.5	30.6
154	1974	12	23	10:04:23	15	146.522	-8.4014	60.4	101.4	66
164	1975	2	7	12:35:00	4	138.257	13.2585	23.3	75.2	43.1
168	1975	3	2	9:59:42	13	161.574	-2.3199	29.9	78.8	66.4
200	1975	10	21	6:17:52	3	31.1018	1.4476	26.5	84.1	37.5
201	1975	10	21	10:07:31	0	94.3829	13.873	66	107.2	87.2
206	1975	11	15	10:21:34	0	151.881	23.0386	72	109.7	91.2
236	1976	2	24	5:58:01	48	172.018	-3.5167	29.1	80.1	41
243	1976	5	12	9:38:20	1	215.49	-19.5852	21.1	77.5	44.7
260	1976	10	28	6:05:22	0	165.191	36.1251	61.8	107	75
273	1976	12	14	8:21:05	0	113.132	31.3317	36	92.7	66.9
292	1977	2	25	2:49:53	43	174.556	14.4521	18.1	82.9	59.4
308	1977	5	22	6:45:07	17	109.045	73.2755	18.8	72.3	50.3
312	1977	6	22	7:35:20	39	272.897	-16.9901	24.2	75.8	44.6
323	1977	8	18	7:36:29	0	324.375	-11.2446	22.1	80.2	45.0
347	1977	11	24	12:43:38	0	68.1496	20.6962	29.4	90.2	48.4
350	1977	12	9	2:05:31	54	34.5213	0.3331	15.5	72.4	43.4
355	1978	1	21	11:03:00	1	30.4374	57.4601	13.9	60.3	34.0
356	1978	2	15	2:04:32	24	145.751	9.8446	20.9	77.1	40.0
360	1978	3	11	8:48:34	0	254.169	53.081	35.3	90.6	56.4
366	1978	4	11	8:28:07	40	203.528	-14.6497	28.2	88	43.8
392	1978	10	15	3:42:46	10	337.394	-24.8421	15.6	73.4	44.5
399	1978	10	31	11:57:50	0	61.3158	14.5358	27.7	85.7	56.4
418	1978	11	20	12:42:13	0	155.024	21.0838	68.2	111	57.2
432	1978	12	3	4:07:35	1	70.7046	42.2932	25.3	87.8	41.1
446	1979	1	20	4:00:26	37	60.4671	36.2917	13.6	78.9	29.5
455	1979	3	27	7:43:17	34	212.038	10.4046	27.1	85.1	33.6
459	1979	6	19	8:41:49	44	25.6862	81.7322	18.0	70.0	37.6
485	1979	9	13	5:26:34	34	6.7344	-2.455	30.7	82.9	43.5
512	1979	11	20	10:48:10	0	154.505	21.3848	73	103.8	78.5
517	1979	11	22	10:42:02	33	352.692	32.8996	15.2	72.9	40.7
538	1980	1	18	4:08:55	40	90.7871	11.0235	16.4	77.9	32.2
548	1980	2	22	4:55:00	48	132.329	-9.5682	19	69.3	39.0

TABLE I
(Continued)

MORP number	Year	Month	Day	Time	Δt (min)	α (deg)	δ (deg)	v_∞ (km/s)	h_b (km)	h_e (km)
554	1980	4	11	8:52:08	46	216.278	-1.1185	32.4	95	41.0
569	1980	7	18	5:17:25	33	275.848	25.296	20.5	69.8	34.2
596	1980	10	5	5:17:55	43	15.831	-16.4914	23.1	78.5	42.4
599	1980	10	12	8:10:46	21	2.8952	22.4349	22.9	86	33.6
644	1980	12	13	11:45:29	0	112.424	32.679	35.8	95.9	42.5
645	1980	12	13	12:36:34	0	112.501	32.3872	36	93.9	55.4
646	1980	12	14	7:15:14	0	113.228	30.2479	36	74.4	41.3
648	1980	12	16	5:44:39	26	61.4386	18.1154	19.4	76.3	40.7
659	1981	2	4	9:11:19	34	104.764	83.3991	17.6	76.3	35.5
663	1981	2	11	9:24:38	54	142.481	18.6568	18.4	66.5	40.2
665	1981	2	24	3:18:10	33	124.253	32.3998	14.2	58.2	37.6
666	1981	3	3	7:34:31	31	290.516	71.2453	20.5	73.7	35.1
676	1981	4	30	7:46:14	26	201.501	-13.4769	22.3	82.9	36.0
677	1981	5	24	8:57:06	52	324.499	66.5454	18.6	69.9	38.1
680	1981	6	20	7:23:21	51	226.082	-19.4981	16.4	74.8	35.5
685	1980	4	14	8:25:22	35	220.901	-3.5056	26.5	80.6	38.1
700	1981	9	7	4:59:47	29	346.577	7.7018	25.3	85.3	39.0
704	1981	9	19	9:50:20	8	356.973	10.3262	31.5	84.3	37.0
705	1981	9	24	4:59:50	29	336.667	12.4243	17.1	78.0	35.3
750	1981	11	23	1:50:00	42	75.5315	17.3633	24.6	82.8	48.6
756	1981	12	6	3:11:51	34	59.3624	5.5425	19.9	72.2	41.0
757	1981	12	7	11:59:46	56	64.6204	8.308	17.4	75.0	55.2
758	1981	12	14	7:19:53	0	112.386	31.1824	36	78.9	47.6
760	1981	12	15	3:52:37	53	153.642	57.4687	21.3	74.5	42.7
783	1982	3	14	3:03:00	0	163.694	40.5729	19.0	77.0	38.7
791	1982	6	2	5:49:34	0	257.515	-17.3074	29.9	100.8	65.4
797	1982	8	8	8:39:25	46	345.589	-21.5128	27.4	84.8	46.3
802	1982	8	13	4:43:10	2	43.1591	59.1259	60	102.8	77.4
816	1982	10	10	7:17:43	0	358.537	-11.5979	18	91.1	48.2
833	1982	11	23	12:06:19	49	45.1008	14.0808	12.7	68.5	36.8
845	1982	12	15	11:38:06	8	77.3424	9.2388	22.5	84.6	37.2
846	1982	12	16	10:22:23	0	90.3776	14.2369	32.6	78.4	40.8
848	1982	12	25	10:10:04	42	89.4447	42.2788	15.1	73.8	32.0
855	1983	1	19	3:38:57	50	102.609	21.2738	18.6	72.7	35.6
856	1983	2	3	2:30:00	10	140.836	6.0964	27.2	83.6	39.6
859	1983	3	8	9:43:40	17	162.3	15.9926	19.1	77.9	39.6

TABLE I
(Continued)

MORP number	Year	Month	Day	Time	Δt (min)	α (deg)	δ (deg)	v_∞ (km/s)	h_b (km)	h_e (km)
903	1983	11	3	8:55:33	25	21.5598	6.3908	19.5	72.4	36.0
912	1983	12	8	0:00:10	49	321.326	59.3578	19.7	72.2	42.4
924	1984	1	25	5:57:54	34	121.126	-20.4975	17.4	73.9	46.9
931	1984	2	11	9:11:42	49	140.276	0.8507	21.1	75.6	45.9
932	1984	3	5	4:33:29	48	87.6757	34.0227	13.8	65.9	33.0
972	1984	11	6	2:36:34	44	271.354	48.8988	21.8	78.5	37.7
998	1985	3	17	12:12:44	10	186.324	2.8361	29.7	88.5	46.2

which orbits have not yet been calculated will likely be depleted in asteroidal material. No photometric calculations were performed on the meteors analyzed here, so it is not possible to give masses, but, given the limiting magnitudes of the systems, they were probably of order grams to tens of grams.

One of the meteors, number 512, has a hyperbolic orbit, but closer analysis shows that it is consistent with the Leonid stream, and the small errors in the orbital elements are responsible for the unbound orbit. Meteor

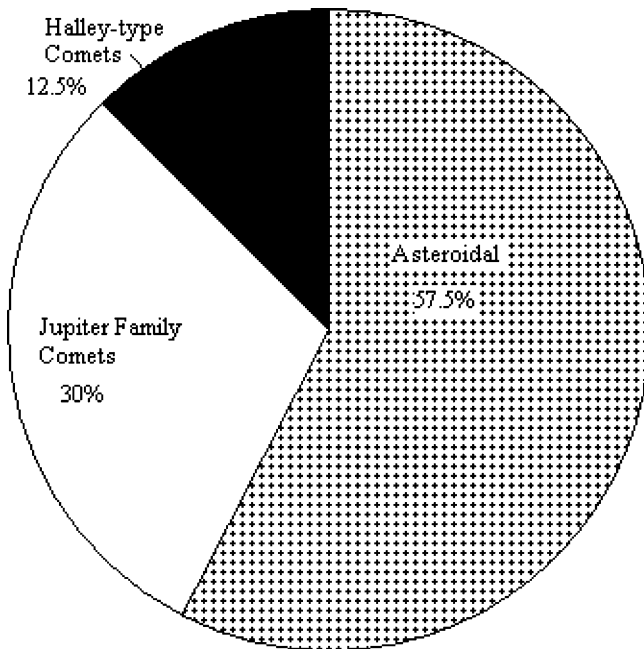


Figure 1. Relative number of objects in three classes.

TABLE II
Orbits of MORP fireballs

MORP number	v_g (km/s)	v_h (km/s)	a (AU)	e	q_{per} (AU)	Q_{ap} (AU)	ω (deg)	Ω (deg)	i (deg)	T_j	Likely type
5	17.343	35.9843	1.773	0.6105	0.6905	2.8555	78.2309	149.216	1.34	4.106	aster
51	40.3194	39.3407	3.4668	0.9645	0.1229	6.8107	141.473	88.9475	22.9625	2.103	JF
84	33.4182	38.7	2.9365	0.9045	0.2805	5.5926	120.437	135.139	10.9189	2.26	JF
127	14.193	34.7923	1.6174	0.5307	0.7591	2.4758	73.3613	340.724	5.9793	3.888	JF
148	11.1381	33.9186	1.3726	0.4261	0.7878	1.9574	250.538	241.607	0.2904	4.37	aster
154	59.286	38.9815	3.1209	0.8581	0.4428	5.7989	100.985	91.5544	130.721	1.094	HT
164	20.7956	37.0462	2.0803	0.7052	0.6132	3.5474	85.1656	138.404	1.8264	3.085	JF
168	27.9536	39.9033	4.4806	0.8879	0.5023	8.4589	92.7851	161.545	8.9408	1.891	HT
200	23.9224	37.9825	2.6119	0.7932	0.5402	4.6836	91.9519	27.5654	8.5173	2.734	JF
201	64.9545	40.2754	5.5346	0.8991	0.5582	10.511	85.8659	27.7407	159.629	0.06	HT
206	70.9279	41.7704	18.0899	0.9456	0.9832	35.1966	171.037	232.767	161.48	-0.859	HT
236	26.6801	32.8464	1.2424	0.763	0.2944	2.1904	128.551	155.09	7.8753	5.018	aster
243	18.1925	37.6381	2.6136	0.7129	0.7505	4.4768	67.4937	232.176	2.8042	2.731	JF
260	60.6369	40.6813	6.768	0.9041	0.6488	12.8871	105.634	215.284	123.412	0.177	HT
273	34.1784	34.1265	1.3905	0.8947	0.1464	2.6346	323.378	262.821	20.667	4.128	aster
292	13.9502	30.1847	1.0069	0.4301	0.5738	1.4399	293.43	336.731	5.6553	6.634	aster
308	15.215	38.0335	2.8993	0.6704	0.9556	4.8431	149.35	61.381	18.3842	2.742	JF
312	21.5383	35.8034	1.9125	0.7042	0.5658	3.2592	274.216	91.0592	4.8036	3.396	aster
323	19.1401	36.0176	1.9468	0.6743	0.634	3.2596	265.898	145.524	1.747	3.243	aster
347	27.4957	38.4231	2.7634	0.8461	0.4252	5.1017	104.138	62.3236	1.2492	2.265	JF
350	10.5408	38.3128	2.6598	0.6478	0.9368	4.3829	28.9345	77.1586	3.541	3.186	aster
355	8.3874	36.6109	1.918	0.4893	0.9796	2.8565	189.592	301.392	8.7786	3.212	aster

TABLE II
(Continued)

MORP number	v_g (km/s)	v_h (km/s)	a (AU)	e	q_{per} (AU)	Q_{ap} (AU)	ω (deg)	Ω (deg)	i (deg)	T_j	Likely type
356	17.3556	35.0573	1.564	0.5818	0.654	2.474	85.3685	146.315	2.064	4.719	aster
360	33.3385	39.1871	3.5456	0.7229	0.9824	6.1089	193.266	350.741	55.439	2.074	JF
366	26.0023	37.1583	2.2773	0.795	0.4669	4.0877	101.868	201.429	4.2936	3.05	aster
392	10.8587	38.8634	3.298	0.7094	0.9583	5.6377	25.0435	21.7275	4.0202	2.737	JF
399	25.6015	30.869	1.0632	0.7683	0.2464	1.8801	136.936	38.0034	7.9957	5.09	aster
418	67.2299	37.9104	2.4738	0.6009	0.9873	3.9603	176.547	238.138	162.094	1.063	HT
432	22.5352	36.653	1.9437	0.7081	0.5674	3.32	271.347	250.953	14.9096	3.574	aster
446	7.7911	36.6573	1.9311	0.5007	0.9641	2.8981	199.999	299.836	3.2406	3.58	aster
455	24.5766	31.88	1.1646	0.6667	0.3882	1.941	301.832	6.35	22.4658	5.216	aster
459	14.0741	31.0919	1.1382	0.2354	0.8703	1.4061	104.304	87.7788	24.1381	5.246	aster
485	28.3849	35.6496	1.8017	0.8264	0.3128	3.2905	121.533	350.136	6.2601	3.508	aster
512	72.0157	42.6554	-37.1951	1.0266	0.9879	-75.378	178.291	237.8	162.803	0	HT
517	10.6005	38.0595	2.5504	0.6247	0.9571	4.1437	203.135	239.84	8.768	2.417	JF
538	11.8809	37.0356	2.0546	0.5721	0.8792	3.2301	44.9832	117.476	4.1145	3.664	aster
548	15.2833	36.7105	1.9886	0.5867	0.8219	3.1553	57.1333	153.013	11.34	3.867	aster
554	30.4495	37.4353	2.4065	0.8505	0.3598	4.4532	293.259	21.9046	15.8498	2.845	JF
569	17.1757	36.9144	2.3153	0.6123	0.8977	3.7328	226.156	116.009	21.4227	3.092	aster
596	20.1108	37.4093	2.3652	0.7128	0.6792	4.0512	76.7344	12.4009	13.1902	2.952	JF
599	20.1633	38.2887	2.8422	0.7544	0.6981	4.9863	252.452	199.446	11.6737	2.371	JF
644	34.1514	34.1527	1.3948	0.8908	0.1523	2.6373	322.574	261.927	23.0106	4.005	aster
645	34.4499	34.2875	1.4153	0.8955	0.1479	2.6827	322.995	261.963	22.914	3.909	aster
646	34.0841	33.9009	1.3579	0.8973	0.1394	2.5763	324.571	262.755	18.6948	4.234	aster

648	15.8736	39.0948	3.2312	0.7474	0.8163	5.6461	53.1533	84.5911	1.1781	2.51	JF
659	13.6455	37.0621	2.0826	0.5377	0.9627	3.2025	201.139	315.76	18.7813	3.136	aster
663	14.8103	34.3932	1.4436	0.5085	0.7096	2.1775	260.41	322.899	1.7408	4.327	aster
665	8.6387	35.7347	1.7203	0.4543	0.9388	2.5018	213.349	335.725	3.0156	4.088	aster
666	17.1074	36.463	1.9289	0.4878	0.9879	2.8698	171.474	342.92	27.6704	3.615	aster
676	19.4747	39.2333	3.9993	0.8095	0.7618	7.2368	62.8943	220.195	2.3141	2.275	JF
677	14.7662	29.8853	1.0331	0.1515	0.8766	1.1896	88.7339	63.3672	27.8138	5.783	aster
680	12.2845	38.3305	3.2058	0.7055	0.944	5.4676	33.8695	269.355	0.6834	2.611	JF
685	24.0724	32.9054	1.2936	0.6975	0.3913	2.1959	298.978	24.8252	11.705	4.744	aster
700	22.566	35.6031	1.7985	0.7155	0.5117	3.0853	280.371	164.755	10.0614	3.621	aster
704	29.6425	40.523	7.1299	0.9364	0.4533	13.8065	277.731	176.635	11.3883	1.186	HT
705	12.8998	35.8032	1.8217	0.5395	0.8389	2.8045	237.787	181.331	7.7144	3.63	aster
750	21.6062	32.4119	1.1887	0.6631	0.4005	1.977	119.423	60.9265	4.7259	5.465	aster
756	16.2317	37.984	2.4779	0.6834	0.7844	4.1714	60.1625	74.1632	6.7646	3.261	aster
757	13.7174	35.5965	1.6611	0.5319	0.7776	2.5447	66.8641	75.5448	5.3212	3.411	aster
758	34.0934	34.1992	1.4014	0.8942	0.1483	2.6546	323.043	262.493	19.9278	4.125	aster
760	17.9961	25.5104	0.7701	0.4402	0.4311	1.1091	326.99	263.361	30.8023	7.702	aster
783	15.1678	38.0876	2.6564	0.6671	0.8843	4.4284	223.636	353.471	12.3271	3.174	aster
791	27.6009	37.8227	2.782	0.8418	0.44	5.1241	283.831	71.6194	5.8654	2.782	JF
797	25.0	30.8603	1.1124	0.7363	0.2933	1.9314	132.523	315.742	16.9427	4.994	aster
802	58.809	41.5423	34.8681	0.9719	0.9784	68.7578	158.505	140.376	111.093	-0.251	HT
816	14.2393	37.8244	2.5628	0.6718	0.8411	4.2844	52.5864	16.9021	4.0304	2.668	JF
833	6.5817	32.4977	1.1975	0.2685	0.876	1.5191	62.3721	60.9213	0.5953	4.401	aster
845	19.8367	37.9985	2.4726	0.7261	0.6771	4.268	75.0508	83.4082	8.2203	2.591	JF
846	30.8225	41.0384	7.4746	0.943	0.4264	14.5228	99.6718	84.3756	10.3102	1.208	HT
848	10.3561	32.6617	1.2033	0.3487	0.7837	1.6229	257.612	273.567	6.1659	4.764	aster
855	14.6727	37.2545	2.1358	0.6242	0.8027	3.4689	58.7621	118.591	0.7013	3.609	aster

Table II
(Continued)

MORP number	v_g (km/s)	v_h (km/s)	a (AU)	e	q_{per} (AU)	Q_{ap} (AU)	ω (deg)	Ω (deg)	i (deg)	T_j	Likely type
856	24.5061	36.2449	1.8235	0.7416	0.4712	3.1759	103.055	133.926	7.8381	4.032	aster
859	15.7477	35.995	1.8038	0.5823	0.7535	2.8542	249.797	347.505	3.7643	3.629	aster
903	16.2192	38.5253	2.9149	0.7283	0.7919	5.0379	58.6566	40.5263	1.1434	2.311	JF
912	16.2625	39.3318	3.4907	0.7193	0.9798	6.0016	189.191	255.562	22.3096	3.112	aster
924	13.3079	32.2621	1.165	0.3431	0.7653	1.5646	82.615	124.671	16.1254	5.468	aster
931	18.0913	34.9388	1.5373	0.5838	0.6398	2.4348	87.3747	142.057	8.235	4.115	aster
932	8.295	38.0322	2.5932	0.6181	0.9902	4.1961	185.512	345.036	2.3023	2.978	JF
972	18.9292	38.9539	3.2519	0.698	0.9822	5.5217	167.987	224.089	27.691	2.689	JF
998	27.7905	37.7112	2.4598	0.8271	0.4253	4.4943	285.37	357.064	5.3915	2.759	JF

number 206 is also a Leonid. The sample also contains one Orionid (number 201), one Perseid (number 802), and five Geminids (numbers 273, 644, 645, 646 and 758). Although a large database of comets, asteroids and meteor showers was searched, no other significant associations were found. In the case of low inclination meteors, many possible associations with near Earth asteroids or Jupiter-family comets were found, but none of these were very close and in all cases were consistent with chance similarities. Backward integration of the orbits may be a more useful technique for determining the most recent parent object of these meteoroids.

The significant number of orbits derived from the MORP data archive will allow a larger systematic search for associations among these bright fireballs than previously done, and also between observed objects and comets and asteroids. Since light curve and trajectory information are available in most cases, these can be used to infer the physical structure and composition of the meteoroids. These in turn can be compared to objects with similar orbits, to determine if the associations are plausible.

Acknowledgements

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BOLIDE ENERGY ESTIMATES FROM INFRASONIC MEASUREMENTS

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Abstract. The acoustic amplitude-yield relationships, including formal errors, for a population of energetic (>0.05 kt) and well-observed bolide events have been investigated. Using various infrasonic signal measurements as a function of range, these data have been calibrated against optical yield estimates from satellite measurements. Correction for the presence of stratospheric winds has also been applied to the observations and is found to be small, suggesting that either scatter is dominated by other variations amongst the fireball population such as differing burst altitudes and greater or lesser amounts of fragmentation or the magnitude of the variability in the stratospheric winds, which can be comparable to or even exceed the strength of the winds themselves. Comparison to similar point source, ground-level nuclear and high explosive airwave data shows that bolide infrasound is consistently lower in amplitude. This downward shift relative to nuclear and HE data is interpreted as due in part to increased weak non-linearity during signal propagation from higher altitudes. This is a likely explanation, since mean estimates of the altitude of maximum energy deposition along the bolide trajectory was found to be between 20 and 30 km altitude for this fireball population.

1. Introduction

Infrasonic sound (0.01 to ~ 20 Hz) produced by large meteoroids (0.1–1 m diameters) entering the Earth's atmosphere at hypersonic velocities has been a subject of interest for many researchers since the occurrence of the 1908 Tunguska blast in Siberia (Ben-Menahem, 1975). Produced either by the shock front of the entering meteoroid or by subsequent fragmentation of the object at altitude, several authors have reported the recording of meteor infrasound by microbarometer arrays in the past (e.g. ReVelle, 1976; Brown et al., 2002a; Pichon et al., 2002). However, until recently the number of microbarometer arrays has been very small. This has changed over the past several years with the construction of the international monitoring network

as part of the Comprehensive Test Ban Treaty Organization (CTBTO) whose purpose is to monitor for nuclear explosions worldwide. Additionally, with the release of U.S. Department of Defense (DoD) and Department of Energy (DoE) satellite optical data for several bolides, it has become possible to calibrate infrasound observations using an independent measurement for the initial energy of the bolide (Brownet al., 2002b).

Historically, observations of infrasound from bolides have been triggered by the ground observations of eyewitnesses (be they casual, photographic or video) and dedicated fireball camera networks. Although these systems remain an important tool for fireball investigation, they suffer from various limitations when attempting to determine the energy of a bolide. Casual eyewitness testimony and photographs often only delimit a bolide's trajectory, without providing velocity information. Eyewitness video offers a potentially much better record, especially in determining velocity, but suffers from issues related to the need for calibration, orientation and light sensitivity (c.f. Boroviča et al., 2004). Dedicated fireball camera networks avoid this continual calibration problem but suffer from the fact that they are stationary systems and must wait for a bolide of sufficient energy to occur nearby. Camera networks also are limited in the total atmospheric area that is monitored making detection of highly energetic events rare. For example, the Canadian Meteorite Observation and Recovery project (MORP) which operated from 1971 to 1985 had the equivalent clear-sky area-time coverage as would be obtained by monitoring the entire globe for 29 h (Halliday et al., 1996). The satellite-based optical sensors of the DoD and DoE combine the best of both worlds, as they cover areas not easily seen by casual observers and have been approximately calibrated for conversion from radiation measured in the silicon bandpass to the total energy of the object (Brown et al., 2002). An outstanding issue in all these calibrations is the unknown applicability of the assumption of a 6000 K blackbody for such large fireball events.

With the public release of DoD and DoE satellite data, it is now possible to study empirically the bolide infrasound phenomena in a way that was never possible before, by cross-calibrating airwave measurements against satellite optical energy estimates, which will provide a means to ground-truth previous bolide infrasound theory.

2. Bolide Data Selection Criteria and Scaling Relations

The database of bolide infrasound has been collected over the past decade using fireball information gleaned from various optical camera networks, published literature and DoD and DoE press releases of satellite observed bolides; a total of ~50 separate bolide events with observed infrasound has

been compiled. For many events, only a single station has detected an infrasonic signal, though a significant fraction (~20%) have been observed by two or more arrays. In addition, for some events, supplemental information is available from independent sources in the form of velocities, optical energy measurements and trajectories/location information. For a few events, meteorites have been recovered on the ground providing the ultimate ground-truth (c.f. Spurný et al., 2003 for an example related to the Neushwanstein meteorite fall) and yet another means to calibrate pre-atmospheric size through radionuclide measurements.

To study the relationship that exists between bolide energy and observed airwave signals, a subset of the bolide infrasound dataset was selected with the goal of removing any possible biases and/or dissimilarities that may exist within the database due to observational range. In particular, only signals observed from a range of >250 km have been included in the subset to isolate only stratospheric arrivals, that is only those waves that have refracted back to the ground at least once from the stratosphere. Similarly, only airwave signals having a minimum average signal velocity >0.28 km/s were included, to remove thermospheric returns (waves refracting to the ground from the thermosphere) (Ceplecha et al., 1998) or stratospheric arrivals with exceptionally strong counter-winds. In general, thermospheric returns were not commonly observed as our average observed range of 3000 km results in severe attenuation for thermospheric returns. Thus all signals in the subset comprise only stratospherically ducted waves.

In addition to these observational range/travel time restrictions, the second criteria for selection was that only those events that have been simultaneously observed by DoD and DoE satellite instruments and infrasound were to be included. This criterion was chosen so that for each event, a quasi-independent method could be used to determine the bolide initial energy or yield and thus calibrate the infrasound energy relationship. This is possible for satellite observed bolides due to the relation determined previously by Brown et al. (2002b) between optical and total energy for bolides,

$$\tau_1 = 0.1212E_0^{0.115} \quad (1)$$

where τ_1 is the integral luminous efficiency and E_0 is the optical energy (in kilotons of TNT equivalent) measured by the satellite sensors assuming that the bolide emission is that of a blackbody with a temperature of 6000 K (Tagliaferri et al., 1994).

After determination of each bolide's initial energy with the associated satellite optical sensor data and Equation (1), a scaling method for comparison of events with different energy observed at differing ranges for air-wave data is required. The energy scaling used is adopted from the empirical

results obtained during investigations of free-air nuclear blasts in the 1950s and 1960s. A detailed version of this scaling law is given by ReVelle and Whitaker (1997) relating range and energy directly to the overpressure, which in the linear regime has the form

$$\Delta p = C \left(\frac{p_0}{p} \right)^{-2/3} R^{-1} W^{1/3} \quad (2)$$

where C is a constant, p_0/p is the ratio of pressures at the source and observation altitudes, and R and W are the observational range and source energy (yield), respectively. Treating all quantities except range and yield as constants in Equation (2), and substituting the satellite energy estimates and range, we define a scaled range for each bolide infrasonic observation as

$$R_s = \frac{R}{W^{1/3}} \quad (3)$$

where R is in kilometres and W in tons of TNT equivalent energy. This scaling of the range requires the assumption that at distances greater than the energy deposition length of a moving point source, the source may be approximated by a point source release of energy from a specific altitude (an assumption used to derive Equation (2)).

The physical reasoning behind this scaling of range in Equation (3) comes primarily from the geometry for a point source explosion. If a point source is located at an altitude with pressure, p_0 , then the energy released will be distributed initially over a sphere of radius R_B , where

$$R_B = \left(\frac{W}{4/3\pi p_0} \right)^{1/3} \quad (4)$$

This is described as the blast radius of the source, physically interpreted as the zone in which all wave energy propagates in a highly non-linear (shocked) state. Since quantities such as the initial overpressure and the fundamental wave period are proportional to R_B , the scaling factor of $1/3$ will tend to appear in the observations of point source type explosions. For many bolides, the majority of the energy deposition occurs over a short length of their total trajectory, often near the end of their luminous flight, so comparison with point-source explosions is valid. This also assumes that the size of the explosion is small when compared to the scale height of the atmosphere (~ 7 km). For very large explosions this relationship breaks down as the spherical symmetry of the source is lost and internal gravity waves begin to

dominate the atmosphere's response. For most bolides however gravity waves are not the dominant type of observed wave.

3. Measurements, Wind Correction and Results

For each infrasonic observation of a bolide (Table I), several quantities of the waveform were measured after stacking and averaging of the waveform by phase aligning signals measured across the array. Measured quantities included (1) the maximum amplitude of the signal envelope computed from the Hilbert transform of the signal (Dziewonski and Hales, 1972), (2) the maximum peak to peak amplitude of the signal within the maximum signal envelope and (3) period at maximum amplitude computed from the four zero crossings at the location of the peak to peak amplitude in the signal. Computed quantities included (4) an estimate for the infrasonic signal energy or power through summation of the squared amplitudes of the bolide signal from which was subtracted the average of the noise power of equal duration prior to and after the bolide signal and (4) an estimate of the signal to noise ratio as determined from the bolide signal and noise power. It should be noted that the signals reported to have been detected from the Tagish Lake fireball (Brown et al., 2002c) have not been included in the present dataset (Table I). After reexamination of the airwave data and signal properties it was found that Tagish Lake was an extreme outlier in all cases. Indeed, it is probable that these reported airwaves are not associated with the Tagish Lake fireball.

Plotting these measurements as a function of scaled range in log-log space, it was found that nearly all followed a generally linear trend consistent with a power law. Only the period at maximum amplitude showed no dependence upon scaled range. However, these power law trends show significant scatter at all scaled ranges and linear regression of the bolide data display poor fits with r squared (the correlation of the least-squares fit) values ranging between 0.262 and 0.460 (integrated signal energy and signal to noise ratio, respectively) where an r squared value of unity represents a perfect fit. This scatter is due in part to the effects of strong atmospheric winds present in the stratosphere and on modification of the signals during the propagation of the infrasonic signals from their respective source bolides.

To correct for the presence of strong stratospheric winds, the correction factor used by Whitaker (1992) while studying infrasonic propagation from the Miser's Gold high explosive test, is adopted. This correction has the form

$$A_W = 10^{k_W} A \quad (5)$$

TABLE I
Bolide events for which optical satellite sensor data (E_o) has been published and stations where associated infrasound has been observed

Bolide	Event date	Event time (UT)	Observing station	Arrival time (UT)	Average HWM winds (m/s)	Satellite optical energy (J)	Reference
Park Forest	27/03/2003	05:50:25	I10CA	06:38:00	25.9	1.42E+11	Brown et al. (2004)
Eastern	23/07/2001	22:19:00	Blossom Point	06:56:15	-17.8		
US Bolide			Blossom Point	22:37:52	-7.6	1.27E+12	1
Pacific	23/04/2001	06:12:00	I59US	08:21:23	1.2	4.6E+12	Brown et al. (2002a)
Bolide #1							
			DLIAR	08:39:25	3.3		
			SGAR	08:09:27	2.3		
			I26DE	16:25:52	1.8		
			NTS	07:54:52	2.0		
			I57US	07:47:56	2.5		
			I10CA	09:54:22	3.0		
			NVIAR	07:52:43	1.4		
Pacific	25/08/2000	01:12:25	I59US	05:53:16	29.3	1.4E+12	Brown et al. (2002a)
Bolide #2							
			DLIAR	03:24:31	2.0		
			I10CA	05:04:30	-5.7		
			PDIAR	04:08:17	4.1		
Moravka	06/05/2000	11:51:50	I26DE	12:11:27	7.6	2.5E+09	Brown et al. (2003)
El Paso	09/10/1997	18:47:15	DLIAR	19:20:00	7.9	1.9E+11	Hildebrand et al. (1999)
							ReVelle et al. (1998)

In addition average HWM wind component along the connecting source – receiver great circle path used in data corrections are given for each station. 1- <http://aquarid.physics.uwo.ca/~pbrown/usaf.html>

where A is the measured quantity, w is the component of the wind vector along the propagation path and k is a constant to be determined from the data. For a value of the component of wind we use an average of the peak wind component between 35 and 60 km altitude sampled every 25 km along the great circle path that connects the source bolide to the infrasound receiver as computed by the Naval Labs Horizontal Wind Model (HWM) (Hedin et al., 1996), as opposed to the SCI component (Webb, 1966, p. 140) used by Whitaker (1992). Note that for this application a positive component is defined as a wind vector pointed in the same direction as the vector going from source to receiver.

Applying this correction for a range of values for k , these data were regressed iteratively for each k until a peak in the r -squared value was found corresponding to the lowest total scatter in these data. Using this procedure r squared values increased significantly from 20% (signal to noise) to 50% (integrated signal energy) with k values of -0.0181 s/m for both maximum signal envelope and peak to peak amplitudes, -0.0369 s/m for integrated signal energy and -0.0106 s/m for signal to noise ratio. Note that the k value for integrated energy (power) are nearly identically twice that of the independently measured amplitude's value for k , consistent with power being proportional to the square of amplitude. This is a reassuring check that this wind correction is not simply a statistical convenience, but that it has its basis in a physical effect.

With wind corrections applied to each infrasonic observation, the power-law curves, along their respective confidence bounds, are obtained (Figures 1–4). The remaining scatter around the calibration curves may in large part

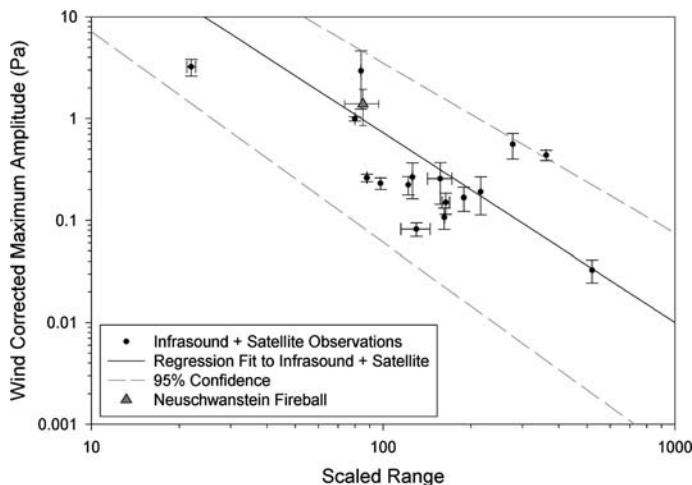


Figure 1. Wind corrected maximum amplitude of the signal envelope for bolide infrasound. $r^2 = 0.584$.

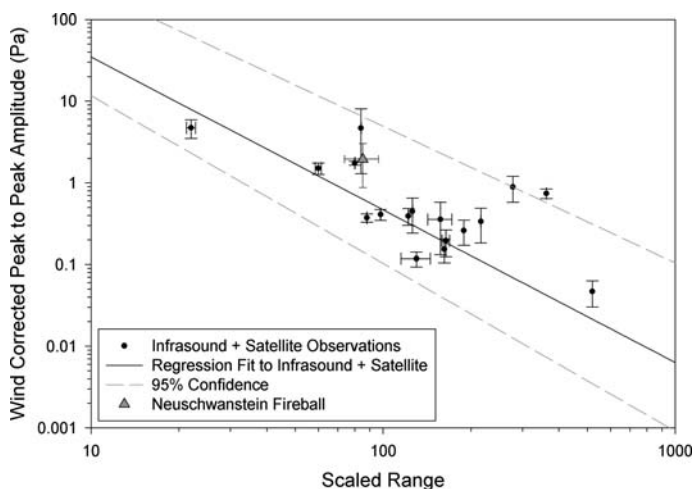


Figure 2. Wind corrected peak to peak amplitude for bolide infrasound. $r^2 = 0.607$.

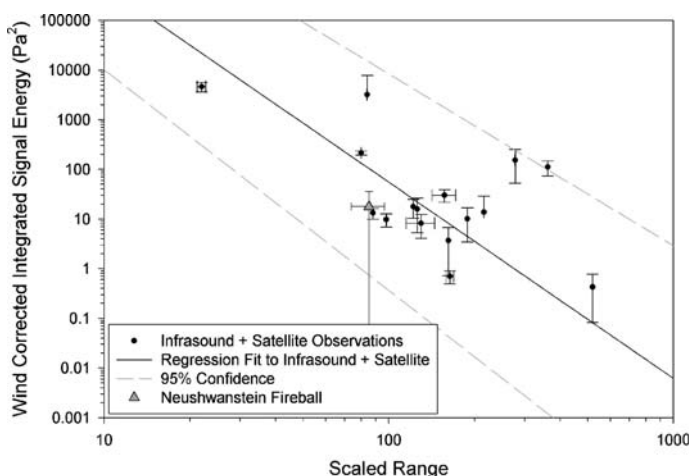


Figure 3. Wind corrected integrated signal energy/power for bolide infrasound. $r^2 = 0.480$.

be due to the uncertainty in the modelled stratospheric winds used. The wind correction term depends greatly on HWM providing accurate wind estimates to the actual wind conditions present at the time of an event, this may or may not be the case for all observations, particularly those that show the presence of strong winds where the correction is greatest (e.g. Park Forest). Finally, from the regression curves and Equation (3), it becomes possible to invert for the bolide source's initial energy directly from the infrasonic observation, these equations have the form:

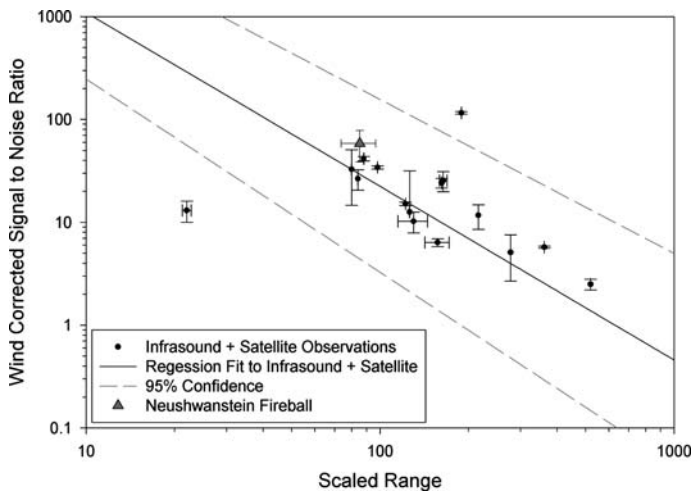


Figure 4. Wind corrected signal to noise ratio for bolide infrasound. $r^2 = 0.548$.

$$W = 10^{-3(a+bw)/c} R^3 A^{3/c} \tag{6}$$

where R is range in kilometres and W is the initial bolide energy in tons of equivalent TNT (1 ton equivalent. TNT = 4.185×10^9 J), A is the infrasound signal property, while a , b and c are the regression constants and wind correction constant specific to each measured quantity (Table II).

4. Discussion and Conclusions

As an independent check on the satellite-observed energy calibration, the observed infrasound from the recent Neushwanstein fireball at the Freyung, Germany array (I26DE) was plotted alongside satellite + infrasound data using a bolide energy as calculated from the initial velocity and mass estimates of the meteoroid determined by Spurný et al. (2003). In all four measurement curves (Figures 1–4), the Neushwanstein data falls very near

Table II
Regression constants and wind correction factors found for each bolide infrasound signal property

	Max amplitude of signal envelope (Pa)	Peak to peak amplitude (Pa)	Integrated signal energy/power (Pa ²)	Integrated energy signal to noise ratio
a	3.41 ± 0.48	3.58 ± 0.46	9.64 ± 1.2	4.73 ± 0.46
b	0.0181 s/m	0.0181 s/m	0.0369 s/m	0.0106 s/m
c	1.87 ± 0.20	1.86 ± 0.19	3.95 ± 0.49	1.69 ± 0.19

the satellite + infrasound regression curve, providing confidence that the choice of bolide energy as computed from optical luminous efficiency is robust.

Now that it has become possible to examine bolide infrasound in a statistical sense, a comparison to similar man-made impulsive sources of infrasound in the atmosphere may provide insight into aspects of bolide infrasound that may be unique to this type of natural source. If the regression fit to the bolide peak to peak amplitude is compared alongside similar data from nuclear and high explosive data for standard 1 kt and 2500 lbs (1134 kg) yields, respectively (Reed, 1977), it is found that the bolide curve is significantly steeper and lies beneath both curves in the region where most bolide data are available (Figure 5). Thus it appears that bolide infrasound is more effectively attenuated than man-made explosive infrasound and is commonly observed at lower amplitudes than might otherwise be expected.

One possible explanation of this discrepancy between nuclear-high explosive and bolide infrasound may be the generally higher altitudes from which bolide infrasound is generated. Nuclear and high explosive data have commonly had sources at or near ground level, while in contrast typical bolides have terminal points at a range of altitudes from 15 to 40 km. Higher source altitudes for infrasound requires that as the waves conserve energy in propagating from altitude to the surface through an increasingly dense atmosphere, the signal amplitudes should decrease. Thus when detected at the surface the amplitude is smaller than would be expected for an equivalent

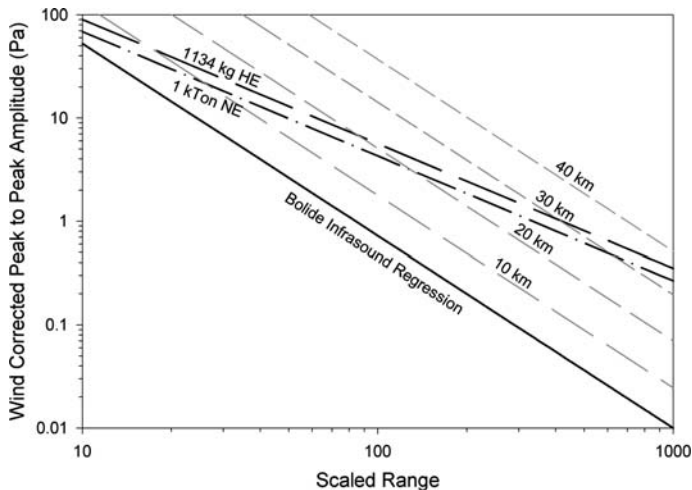


Figure 5. Comparison of bolide peak to peak amplitude to similar empirically derived curves for a 1 kt ground-level nuclear explosion and 1134 kg HE explosion. Note: In nuclear explosions approximately half the energy goes directly into radiation hence 1 kt NE $\sim$ 0.5 kt HE equivalent acoustic yield.

surface source. This source altitude effect means that treating the p_0/p term as a constant in Equation (2) is incorrect, instead the magnitude of this term may vary between events as the various bolides detonate at varying altitudes.

As the bolide curve represents an average of all the observed bolide infrasound events, we may apply the p_0/p correction for various source altitudes and produce an estimate for the average altitude for bolide infrasound energy deposition. Applying the p_0/p term to the bolide curve using pressure values from the 1978 U.S. Standard Atmosphere (U.S. Committee on Extension to the Standard Atmosphere, 1976) for altitudes of 10–40 km, it is observed that the “corrected curves” cross the nuclear/high explosive curves between the altitudes of 20 and 30 km (Figure 5). This altitude interval corresponds well with observed terminal altitudes for 0.1–1 m diameter bolides (e.g. Docobo and Cep-lecha, 1999; Borovička and Kalenda, 2003).

The differing slope between the bolide curve and explosion values is possibly a consequence of the deeper penetration for more energetic bolides. These bigger events will generally occur at smaller scaled ranges; indeed nearly all events with scaled range less than 126 km have total yields determined from satellite data of > 0.5 kt. Penetrating deeper into the atmosphere they will have less attenuated amplitude signals and this be closer to the “ground” curves. Ideally one would like to evaluate this correction directly from observations; unfortunately the terminal altitudes for most of the observations in the current dataset remain an unknown parameter. Instead an alternative approach would be to separate the large and small events and evaluate their slopes independently as a test of the deeper penetration hypothesis. However this test must wait for the number of observed bolides to accumulate as the dataset still somewhat limited in the number of very energetic events.

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THE MODELING OF BOLIDE TERMINAL EXPLOSIONS

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Abstract. The phenomenon of terminal thermal explosions of bolides is considered and mathematically modeled, using the mechanisms of ablation and fragmentation due to mechanical and thermal stresses. The definition and criterion of thermal explosions are given. An analytical solution is obtained for the model of ablating and mechanically fragmenting meteoroid motion in the atmosphere. Numerical calculations including the terminal stage of the motion are fulfilled for the Tunguska parameters. They demonstrated a very rapid energy loss, corresponding to the terminal flare and full mass loss, explaining the absence meteorites.

Keywords: Bolides, fragmentation, meteorites, meteoroids, terminal flares, thermal explosion

1. Introduction

The existence of the phenomenon of terminal flares or explosions of bolides is known in Physical Theory of Meteors (Bronshten, 1983; Ceplecha et al., 1998). Professional and amateur observers regularly register flares. For example, according to the latest reports of American Meteor Society more than 20% of meteors demonstrate terminal flashes. Characteristic durations of the flares are of the order of fractions of a second. There can be several flares during meteoroid flight. They usually correspond to intensive (tens of percents) but not total mass loss. There are a number of works, devoted to the discussion of bolide terminal explosions (see i.e. Levin and Bronsten, 1986 and ref. therein). Data of the Prairie and European Networks on fireballs with terminal flares were collected by Sekanina (1983). Thus far, there is no satisfactory physical explanation of the very phenomenon and the absence of meteorites on the surface of the planet after it. The present paper is devoted to physical–mathematical modeling of terminal explosions connected with full mass loss of the body. The suggestion of the paper is that the phenomenon is due to combined action of thermo-mechanical fragmentation and ablation of fragments. We believe that both the preliminary mechanical fragmentation of the meteoroid and the mechanism of thermal stresses play important roles.

2. The Criterion of a Terminal Thermal Explosion

Thermal explosion is a very fast energy transfer to the atmosphere with the conversion of the whole body mass into vapor. Words “very fast” mean in fractions of a second, in a narrow interval of heights (less than 1 km). Thus, there are two conditions, which must be satisfied, in order we could say that a thermal explosion of a bolide took place. The first one is the fast energy transfer to the atmosphere; the second is the total mass loss of the body.

The efforts of mathematical modeling of terminal explosions have been done since the 1950s. The first papers (Smith, 1954; Pokrovsky, 1966) considered qualitatively the process of catastrophic fragmentation as an explosion. Quantitative model of such fragmentation was developed by Grigorian (1979). An effect of a very intensive mass loss was achieved by some strong assumptions in (Petrov and Stulov, 1975) and using the idea of porosity in (Liu, 1978). But none of the listed models explained both the rapid energy deposition and full mass loss of the body. Purely gasdynamical considerations were made by Shurshalov (1984) and Kondaurov et al. (1998), but they were not connected with the previous conditions of meteoroid motion. So, the description of the coordinated scenario of meteoroid interaction with the atmosphere including terminal stage remained to be an open problem.

The thermal explosion criterion was formulated by Liu (1978) as follows:

$$\tau_m/\tau_b \ll 1, \quad (1)$$

where characteristic ballistic time $\tau_b \sim \frac{h}{V \sin \theta}$, h is the scale height, V is the meteoroid velocity, θ is the trajectory inclination angle to the horizon; characteristic time of full mass loss $\tau_m \sim \frac{M}{\sigma G \rho V^3 A}$, G is the drag coefficient, σ is the ablation parameter, ρ is the air density, M and A are the total mass and the cross section area of the body correspondingly.

Condition (1) rewritten using expressions for τ_m and τ_b implies that some combination of variables must be much smaller than some time interval, which, in turn, varies in a wide range depending on the meteoroid velocity and entrance angle. Physically it means that the ablation goes much quicker than the deceleration.

In the present paper we formulate the criterion of thermal explosion in terms of meteoroid kinetic energy $K = MV^2/2$:

$$\frac{dK/dt}{K} \gg 1 \text{ s}^{-1}. \quad (2)$$

The physical meaning of expression (2) is that the process of energy loss takes very short period of time (less than 1 s), independently of the duration of the body motion. And the same combination of variables as for the first

case must be much smaller in comparison with the fixed time interval of the order of a second.

3. Meteoroid Mechanical Fragmentation

From our point of view at least two mechanisms are responsible for the realization of condition (2). The first one is the mechanical fragmentation due to the aerodynamic load ρV^2 . The ideas of the model, analytical solutions and their consequences are presented in another paper by the authors. Here we cite concisely only its general ideas.

Fragmentation starts, when ρV^2 exceeds the strength limit of the body σ_* , which is defined according to statistical theory of strength (Weibull, 1939):

$$\sigma_* = \sigma_e \left(\frac{M_e}{M_*} \right)^\alpha, \quad (3)$$

where σ_e is the initial strength of the body, M_e is the initial mass, M_* is the total mass at the moment of fragmentation, α is an empirical scale parameter, characterizing the homogeneity of the meteoroid material (the more homogeneous body, the less the value of α). According to relation (3), the strength of the fragment is larger, the smaller its size. While the aerodynamic load is growing, the fragmentation goes on. Following Fadeenko (Fadeenko, 1967) we assume all fragments to be identical, i.e. having one and the same mass equal to $M_f = M/N$, where N is the number of fragments. If we apply condition (3) to each fragment of mass M_f and strength σ and take into account that $\sigma(\sigma_*)^{-1} = \rho V^2 (\rho_* V_*^2)^{-1}$ we obtain:

$$N = \frac{M}{M_*} \left(\frac{\rho V^2}{\rho_* V_*^2} \right)^{1/\alpha}. \quad (4)$$

The subscript star is used in (4) and below for the values of variables at the moment of fragmentation beginning. The values of α , σ_e and M_e are assumed to be known. Formally, N may be noninteger, but its integer part should be taken when this number is determined.

The equations of drag and ablation of fragments conglomerate have the same forms as in the classical physical theory of meteors (Bronshten, 1983) with the total cross section area depending on N :

$$A = f \left(\frac{M}{\delta} \right)^{2/3} N^{1/3}, \quad f = \frac{1}{N} \sum_{k=1}^N f_k,$$

where δ is the meteoroid density, the shape factors of all of the fragments $f_k = 1.21$ (spheres), so $f = 1.21$ too.

This statement of the problem of progressively fragmenting meteoroid deceleration and ablation allows the following analytical solution:

$$V = V_* \left[1 + \frac{\bar{\rho}_*}{1 + 3\alpha} \left(\left(\frac{\rho}{\rho_*} \right)^{\frac{1}{3\alpha} + 1} - 1 \right) \right]^{\frac{-3\alpha}{2}}, \quad (5)$$

$$M = M_* e^{\frac{g}{2}(V^2 - V_*^2)}, \quad (6)$$

where $\bar{\rho}_* = \frac{h\rho_* 2GA_*}{M_* \sin \theta}$, the scale height h , the trajectory slope to the horizon θ ; the ablation parameter σ , the drag coefficient G are constant.

The convenient analytical form of solution (5–6) makes it possible to find all the characteristics of meteoroid fragments at any moment, in particular, the sizes of fragments. They are important for the evaluation of thermal stresses imposed, which represent the second mechanism involved for the physical explanation of the explosion phenomenon.

4. Thermo-stresses

The heat equation in a spherical body of radius R with zero initial temperature and constant surface temperature T_W equal to the temperature of the surrounding medium has the solution, which represents the temperature distribution as (see e.g. Koshlyakov et al., 1970 or Tikhonov and Samarskiy, 2004)

$$T(r, t) = T_W \left\{ 1 + \frac{2R}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \left[\sin \frac{\pi n r}{R} \exp \left(-t \chi \left(\frac{\pi n}{R} \right)^2 \right) \right] \right\},$$

where χ is the temperature conductivity ($\chi \sim 10^{-1} - 10^{-2} \text{ cm}^2 \text{ s}^{-1}$ for iron and stony meteoroids), t is the time, r is the radial coordinate counted from the center of the sphere, so $r = R$ corresponds to the sphere surface. In more accurate statement boundary condition should include thermal radiation from the particle surface, which makes the problem nonlinear and requires numerical solution. Since we use the solution only for estimates of stresses, we remain in the frames of the simplified statement and leave its exact consideration for future works.

Temperature gradients inside the body are the reasons of thermo-stresses. The distributions of radial and tensile stresses inside a sphere are (Hopkinson, 1879):

$$\sigma_r = \frac{2\beta E}{3(1 - \varsigma)} [\bar{T}(R, t) - \bar{T}(r, t)], \quad (7)$$

$$\sigma_\tau = \frac{2\beta E}{3(1-\varsigma)} \left[\bar{T}(R, t) - \frac{3}{2} T(r, t) + \frac{1}{2} \bar{T}(r, t) \right], \quad (8)$$

where β is the thermal expansion coefficient, E is the Yung module, ς is the Poisson coefficient, $\bar{T}(r, t)$ is the average temperature for the internal part of the sphere of radius r , defined as $\bar{T}(r, t) = \frac{3}{r^3} \int_0^r r'^2 T(r', t) dr'$. So, (R, t) is the average temperature of the whole sphere.

The analysis of $\sigma_r(r)$ and $\sigma_\tau(r)$ fulfilled in Grünberg (1926) has demonstrated that both these functions have their maxima in the center of the sphere. $\sigma_r(r)$ equals to zero, as it is easily seen from (7). $\sigma_\tau(r)$ is the minimum.

$$(\sigma_r)_{\max} = (\sigma_\tau)_{\max} = \frac{0.385\beta E}{1-\varsigma} T_W, \quad (\sigma_\tau)_{\min} = -\frac{\beta E}{1-\varsigma} T_W. \quad (9)$$

The absolute value of the minimum is larger than the value of both maxima. The minus sign in the last equality of (9) means the tension of the body. Expression (9) do not depend on body size, but the times of these extremes achievement are proportional to the radius of the sphere and have the order of $t \cong R^2 \pi^{-2} \chi^{-1}$. So, only a thin near-surface layer of large bodies will be heated, but small bodies ($R \rightarrow 0$) will be heated through almost instantaneously. Exact value of fragment size, for which the mechanism of thermo-stresses will work, depends on physical and mechanical properties of the meteoroid material. Fragments of cometary material may be crushed by thermal stresses, if their sizes are of the order of parts of a millimeter. Iron fragments must have the sizes of several centimeters.

Using mechanical characteristics of meteoroid materials (Medvedev et al., 1974) and surface temperature of the order of boiling one, that is ~ 3000 K, the evaluation of $(\sigma_r)_{\max}$ and $(\sigma_\tau)_{\min}$ gives the values of ~ 3000 atm. For Tunguska-like body fragments strength may be as low as several tens of atmospheres. So, thermal stresses will cause further fragmentation up to the sizes of dust, which will rapidly evaporate and, thus, two conditions for the thermal explosion will be satisfied.

5. Calculations results

We have considered fragmentation process due to thermal stresses according to the same scheme as for the mechanical fragmentation and we have fulfilled numerical calculation of the fragments further deceleration and ablation. It is worth mentioning here, that we used variable ablation parameter in our calculations, defined on the basis of gasdynamic consideration. As it is well known and as it is confirmed by the calculations, radiation is the main mechanism governing the fragments ablation in continuous flow regime. The

role of radiation is greater the smaller is the particle. After thermal fragmentation the pieces are small enough to be totally ablated by radiation. So, the body is “prepared” by mechanical and thermal fragmentation and then evaporated by radiative heat transfer.

The curve for the total energy loss on the trajectory is presented in Figure 1. For comparison analogous curves are given for the single body model (Figure 1a) and for the model of only mechanically fragmenting body (Figure 1b). Parameters of Tunguska were used in the calculations: $V_e = 35 \text{ km s}^{-1}$, $I_e = 10^9 \text{ kg}$, $\theta = 30^\circ$, $\delta = 10^3 \text{ kg m}^{-3}$; $\sigma_e = 1.7 \text{ atm}$ and $\alpha = 1/6$ were defined from the observational data for the altitudes of fragmentation beginning and termination. The average value of the variable heat transfer coefficient is 0.2, of the ablation parameter is $4 \times 10^{-3} \text{ s}^2 \text{ km}^{-2}$.

It is seen that the maximum of the curve at Figure 1b and even more so the maximum of the curve at Figure 1a are far from being narrow. And only Figure 1c demonstrates an instantaneous energy deposition to the atmosphere at some point of the trajectory, which is one of necessary conditions for the explosion. The second condition of the total body mass loss was also met, but the plot is not shown here.

6. Discussion

The phenomenon of terminal explosions of bolides was considered. The criterion of thermal explosion was formulated. The physical-mathematical model of the phenomenon was offered and used in simulations. It demonstrates the fulfillment of the explosion criterion conditions and allows rea-

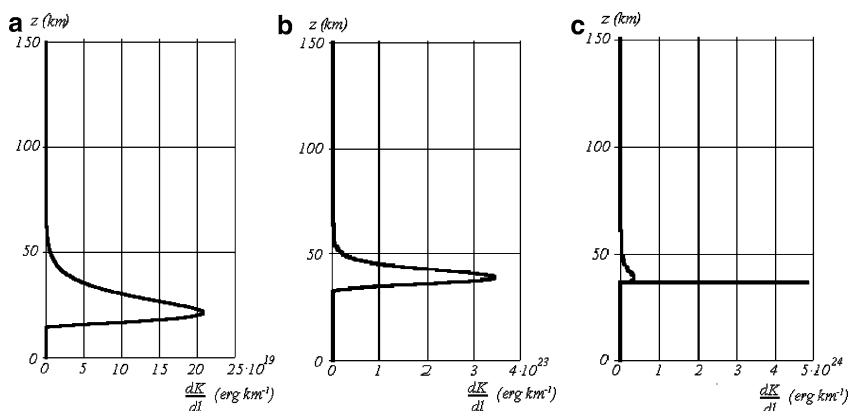


Figure 1. The change of energy deposition to the atmosphere with height. (a) single body model; (b) mechanically fragmenting body model; (c) mechanically and thermally fragmenting body model.

sonable explanation of bolide flares and the absence of meteorites on the surface of the planet after them.

The model assumes independent motion of the fragments, while some time is required for their separation. It puts a restriction to the application of the model for extremely large bodies (with sizes of tens of meters) and small values of α (close to zero). Restriction dealing with body sizes is given in (Svetsov et al. 1995). The separation of fragments was considered in (Khanukaeva, 2002) for various values of α and formulated in terms of the delay before fragments origination. The estimates made for 1 m-sized body gave 2–4 km shift in altitudes of fragments appearance after the fragmentation condition realization. We neglected this delay in the present work. More accurate consideration should include the stage of interacting fragments motion and may represent further development of the model.

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OPTICAL OBSERVATIONS OF METEORS

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Abstract. Optical observations remain the most widely used method for studying meteors, even though they are limited by daylight and weather conditions. Visual observations have been used throughout history. They lack the precision of other methods, since they rely on the judgment of observers for trajectory information. However, since no special equipment is required, visual observations are widespread, and can give valuable information on the activity profile of showers. Photographic observations are much more precise. Rotating shutters allow velocities to be determined, and networks of cameras permit the height and trajectory of a meteor to be calculated. Except for the Super-Schmidt observations at Harvard, most photographic observations record only meteors brighter than 0 magnitude. Video observations, using image intensifiers, can record much fainter meteors down to +7 magnitude. Processing is becoming very automated, so that large quantities of data can be reduced relatively easily. Most video cameras have much lower precision than photographic cameras, but new technologies are changing this. Spectral observations of meteors, using video or photographic techniques, can be used to investigate the chemistry of meteoroids, while telescopic observations allow measurements to be extended to much fainter meteors (+10 or fainter).

Keywords: Meteors, photographic, video, visual

1. Introduction

Optical observations of meteors have historically produced many advances in the field of meteor physics, and are expected to contribute to many more advances in the future.

The two major branches of meteor observation are optical and radio. The main difference between the two is the capability of radio observations to observe during daytime and through clouds, but typical optical systems have certain advantages over typical radio systems. Radio systems range from simple receivers, capable of detecting reflections from commercial broadcasts by forward scatter, through backscatter patrol radars optimized for meteor observations, to high-aperture radars with very small fields of view and high accuracy. Forward scatter systems, while widely available (a radio tuned between local stations can be used) cannot generally be used in the calculations of fluxes. High-aperture radars like Arecibo have very high (MW) transmitter powers and have high meteor rates but tend to see

overwhelmingly very faint meteors. Patrol radars are most useful for shower observations and for observations of the sporadic complex for meteors brighter than +9 magnitude. They can produce thousands of orbits in one day, but the precision of these orbits is much lower than for photographic techniques, and backscatter systems are biased against high, fast meteors. Optical systems are not yet as automated as meteor patrol radars, but are preferred in situations where high accuracy is required (for example, when back integration on the orbit of a shower meteor is to be performed). Optical systems are also capable of giving spectral information, which is vital in investigating the chemical composition of meteoroids. Certain types of optical systems, including some photographic and video systems, are widely available, increasing the global coverage of meteor observations.

The oldest form of meteor observing is obviously visual; visual records of meteor observations date back at least two millennia, with recent compilations of ancient meteor shower activity observed visually providing an important constraint for the modeling of many meteoroid streams. While visual observations generally have low accuracy, they can provide very large, useful datasets. They remain the most useful means to gauge shower flux and activity. Photographic and video observations have taken over from visual observations in the last century as the preferred form of observing individual meteors, yielding precise radiants, speeds, orbits and trajectory information. The addition of a prism or diffraction grating allows the spectra of meteors to be measured, which is useful in determining the chemical composition of meteoroids. Meteoroids which penetrate all the way to the surface of the Earth are of particular interest, since their physical properties can then be measured directly: all of the above optical methods can be used to calculate orbits and obtain information about the interaction between the meteoroid and the atmosphere.

While limited by weather and daylight, optical observations have been and will continue to be of great usefulness in solving many outstanding questions about meteoroids and their origins.

2. Visual Observations

People have been observing meteors with their eyes throughout recorded history. Chinese records go back the longest (see Imoto and Hasegawa, 1958 for a summary of Chinese, Japanese and Korean records), but many other records exist (cf. Rada and Stephenson, 1992 for observations in Arab chronicles). Two German students, Brandes and Bezenberg, performed the first dual-station observations of meteors in 1798, and determined that meteors occur at a height of 100 km. This established that they were an upper

atmospheric phenomenon, consistent with extra-terrestrial stones colliding with the atmosphere.

The most basic visual observation involves a simple count of the number of meteors seen by a particular observer in a particular time interval, with a corresponding limiting magnitude and brightness distribution. This may be divided into meteors consistent with active shower radiants, and sporadics, which are not consistent with known radiants. It is not possible to identify a shower meteor absolutely from a single observation (though knowledge of shower velocity and a measurement of the angular speed and angular distance from the radiant can be used as a strong discriminant), but statistically the numbers will be representative of each population. More experienced observers may plot the paths of observed meteors on a map, or measure the coordinates of the beginning and end to a recorder. The meteor's brightness and angular speed can also be estimated by experienced observers.

From these observations, the hourly rate of shower and sporadic meteors can be calculated, assuming the limiting magnitude and efficiency of the observer are known (Koschack and Rendtel, 1990). From recorded meteor brightnesses, the population index (a measure of the relative proportions of meteors of different brightnesses) may be calculated, allowing corrections to fluxes at different limiting magnitudes (see Rendtel and Brown, 1997 for details of flux calculations, including collecting area for a typical observer). While the accuracy of an individual visual observation may not be high, a large number of observations averaged together generally produce a good estimate of shower activity. Also, there is no need for any advanced equipment in visual observations, so that many experienced amateur observers are able to observe on a regular basis. This produces a large catalogue of data, where differences in the efficiency among observers may be evened out. Visual observations are particularly well suited to flux monitoring, identification of small showers, and calculation of population index as a function of time. They are also useful in calibrating observations in historical records.

Visual observations remain the most useful means to gauge shower flux and activity. The modern era of visual observations make use of standardized counting techniques from observations globally and may result in very precise activity curves. Indeed, it was the identification of an early peak in the Perseid meteor shower from some of the earliest global visual observations in 1988–1989 which presaged the return of comet 109P/Swift-Tuttle (Roggemans, 1989) and marked the beginning of the modern era. This represents a true coming of age in modern visual observations and no other optical technique has proven as reliable for providing long-term flux profiles as visual data. Some of the more recent examples of the usefulness of visual data occurred during the Leonid meteor showers from 1997 to 2002, when enhanced activity was expected from the shower. Visual observations were made around the globe, allowing nearly uninterrupted (ZHR) zenithal hourly rate and

population index data to be calculated. In general, the results were available through the International Meteor Organization's website within hours, giving researchers a valuable comparison for meteoroid stream models and data which helped in the reduction of data collected with other methods. See, for example, Arlt et al. (2001) for analysis of the 2001 storm. Visual observations have also been used to confirm predicted outbursts of meteor showers, like that of the alpha Monocerotids in 1995 (Rendtel et al., 1996) and the Draconids in 1998 (Arlt, 1998), and to detect unexpected outbursts (Hashimoto and Osada, 1998).

Visual observations can also be important in constraining the path of a bright fireball in the atmosphere. Individual observations of a fireball tend to be even less accurate than observations of fainter meteors, since bright fireballs occur at random and take even experienced observers by surprise. The extent and location of the trajectory (particularly the azimuth of the radiant) can, however, be significantly constrained by such observations.

3. Photographic Observations

The first photograph of a meteor was obtained in 1885 (Ceplecha et al., 1998), and many more were recorded accidentally as astronomical photography became more widespread. The first dedicated photographic study of meteors was started by Whipple (1938) at Harvard, where high-quality data were collected over the next two decades. Whipple was the first to successfully use two photographic stations to calculate trajectories for a large number of meteors, including height, speed and radiant; he also equipped the Harvard cameras with rotating shutters which allowed velocities to be calculated. Meteor camera baselines can range from 30 to 200 km, offering different levels of accuracy in trajectory calculations and overlap between the stations. Major fireball networks were subsequently set up in Czechoslovakia (now expanded into the European Network, or EN), in the United States (the Prairie Network, or PN), and in Canada (Meteorite Observation and Recovery Project, or MORP).

So-called classical or small camera photographic observations generally involve bright meteors, brighter than 0^M or -2^M for many cameras. These systems may be all-sky (with a fish-eye lens or hemispherical mirror) or wide field. Wide field systems may require many cameras at a single site to cover the whole sky (for example, the Prairie Network used four cameras per station, and the MORP network five cameras per station). Using several wide field systems generally produces lower limiting magnitudes and higher spatial accuracy than all-sky cameras, but this type of system is also more expensive and may have gaps in sky coverage.

Photographic observations also include the Super-Schmidt cameras operated by Harvard, which were placed in New Mexico and later Alberta, Canada, primarily during the 1940s and 1950s. These cameras were more sensitive than small cameras, seeing meteors as faint as $+3^M$ over a 55° field of view. The surveys carried out with these cameras are still used as a reference for the dependence of height on entry angle, speed, and mass; see Jacchia et al. (1965). These Super-Schmidt data also form the basis for some of the best available measurements on the overall velocity distribution of meteors at the Earth. The cameras' high temporal and spatial precision have also allowed physical properties, such as density, of the associated meteoroids to be measured (cf. Bellot-Rubio et al., 2001). The anomalous shapes of light curves of faint meteors observed with the Super-Schmidt cameras led to the development of the dustball theory (Jacchia, 1955).

Small cameras have also yielded important information on meteoroid structure: because of the very high resolution of photographic plates, decelerations of meteors can be measured quite accurately. McCrosky and Ceplecha (1970) showed that even bright fireballs observed by the Prairie Network had low strengths compared with meteorites, demonstrating that even the structure of these larger bodies was not as simple as the classical model assumes.

Photographic networks can also permit the calculation of the orbit of a meteorite. To date, fireball networks have been responsible for the determination of four meteorite orbits. The European Network (and its predecessor) has observed the Příbram and Neuschwanstein meteorites, in 1959 and 2002, respectively; the Prairie Network recorded the fall of the Lost City meteorite in 1970, and the Innisfree meteorite was recovered after being observed on the MORP network in 1977.

Some of the drawbacks of photographic networks include the fact that they are generally confined to bright meteors or fireballs, and that there is relatively little area covered by networks of cameras compared to that covered by visual observers. For example, the entire atmospheric area-time coverage product of the MORP network from 1971 to 1985 is equivalent to global coverage for just over 24 h.

4. Video Observations

The first video observations (also known as electro-optical or Low Light Level TV) were made in the 1960s (Spalding, 1961). The addition of image intensifiers in the 1970s greatly increased the sensitivity, and therefore usefulness of these systems. The use of video in meteor observations became widespread in the 1980s and 1990s, when the equipment needed became cheaper and analysis easier. Most video systems consist of an image

intensifier coupled to an objective lens and a CCD video camera (which can have digital or analogue output). Typically, such systems have limiting magnitudes between $+3^M$ and $+9^M$, and fields of view ranging from 40° to 10° , depending on the objective lens: video systems can also be used to observe bright fireballs as part of an all-sky system. Newer intensifiers tend to have lower noise, flatter images and more sensitivity in the near IR (for details on the improvements, see Hawkes et al., 2001).

Again, one of the most useful application of video cameras is when the cameras are arranged in pairs, looking at the same portion of sky. Two station analysis procedures are described in Campbell et al. (2000).

The chief advantage of video over photographic observations is in the sensitivity and time resolution of video methods. The resolution of video data is much lower than the resolution of a photograph, but very accurate timing information is available and many more meteor trajectories can be obtained in the same observing time. More complete shower observations can also be made with intensified video, since the increased number of meteors makes flux calculations possible.

Light curves of faint meteors are of interest because they can reveal the structure of small meteoroids, including grain sizes (see Beech and Murray, 2003; Campbell-Brown and Koschny, 2004 for examples). The recent Leonid showers have produced detailed analysis of fluxes (including fine structure), radiant and orbits (e.g. Trigo-Rodríguez, et al., 2004; Brown et al., 2002; Singer et al., 2000). Single station radiant have been measured for many showers by Molau and Arlt (1997). The Leonids were rich in persistent trains, allowing studies of these structures to be performed (Kelley et al., 2000).

In addition to low resolution, multi-station video observations also suffer from a lack of global coverage, and a lack of general patrol data (although a global network of amateur-run automated video intensified cameras has begun operation (Molau, 2001) possibly signaling the beginning of global flux coverage from video data alone; but this network consists primarily of single station observations). In particular, most observations are performed around major showers, and the winter months in particular suffer a lack of trajectory data. This is changing to some degree; digital video cameras are now becoming available which have better resolution than standard video, and the price of basic image intensifiers is dropping to the point where they are used by serious amateurs. Automated video networks capable of generating fluxes, orbits and light curves have not been implemented for many reasons: the relatively short tube life of image intensifiers; the difficulty in analyzing large amounts of video meteors in an automated way, and the difficulty in calculating the limiting magnitude for each system. However, tube lifetimes are improving steadily, as are detection algorithms (see Molau, 1999; Gural, 1995 for descriptions of algorithms). The best algorithms are approaching full-resolution, real time detection of meteors, and analysis

procedures for photometry and astrometry may soon be integrated in such real-time, automated systems.

Camcorders, while not particularly useful for patrol work, are sometimes the only optical record of a bright, meteorite-dropping fireball. Two meteorites have had orbits calculated from camcorder records: Peekskill (Brown et al., 1994), and Morávka (Borovička et al., 2003). If recordings are made from several locations, foreground objects can be used to calibrate the images so that trajectories and orbits can be computed. As personal video recorders become more common, we can expect many more such records. Also increasing in frequency are the recording fireballs by security cameras, such as in the case of the Park Forest meteorite-dropping event (Brown et al., 2004).

5. Telescopic Observations

Traditionally, telescopes have not been used in meteor observations, since the very small field of view of most telescopes often means a long wait between meteors. Observations made by chance in the course of other investigations can be useful (see Pawlowski et al., 2001), but speeds and heights cannot be measured from single station observations. Efforts have recently been to use smaller telescopes; Yanagisawa et al. (2003) attempted to determine the structure of the Leonid radiant with single station observations, and Kaiser et al. (2005) have used two stations to find heights, and therefore widths of faint meteors. Telescopic meteors have the advantage of very high resolution, allowing the measurement of trail widths, fine scale investigations of fragmentation, and fine scale light curves, for meteors down to $+10^M$.

6. Spectral Observations

The first recorded spectrum of a meteor was obtained in 1897, but there was no systematic survey of meteor spectra until that started by Peter Millman at Harvard (Millman, 1932, 1935). Meteors have the advantage of being linear in nature, so that a slit is not required for spectra, but this also means the best resolution in the spectrum is limited by the physical size of the train. The first video spectrum was taken at Dudley Observatory by Spalding (1961), and the advantages of video were immediately recognized, particularly regarding the spectra of meteor wakes and trains, which are not distinguished from the meteor head in photographic spectra. Even though the resolution of video is so much lower than photographic, the increased number of spectra which can be obtained with the more sensitive video systems has made them popular for spectral studies. A more complete history of meteor spectra observations can be found in Millman (1970).

The most obvious use of meteor spectra is to identify atoms which are present in the meteoroid. Many metals and other elements are prominent in spectra taken in the visual range, including hydrogen, sodium, magnesium, silicon, calcium, manganese, nickel, aluminum, chromium and iron (Cook and Millman, 1955; Russell, 1960). Spectra can also be used to investigate the relative proportion of atoms in a meteoroid, by deriving the temperature of the plasma in various parts of the head and wake (Borovička, 1993). Even without complete spectra, spectral information can be used to deduce the composition of meteoroids: for example, by examining light curves in full-spectrum and single wavelength, one can estimate where a particular atom is more likely to be deposited (e.g. Murray et al., 1998, who investigated light curves in visible and sodium wavelengths).

Recently, lidar systems have been used to investigate meteor trains. These systems excite metal atoms or ions at resonant wavelengths and produce a measure of the abundance of the metal in the train. A large survey of trains (von Zahn, 2001), measuring sodium, potassium, iron, calcium and calcium ions showed evidence for differential ablation of meteors. The technique is used only on trains, not on the hot plasma of the head, since the probability of a meteor passing through the lidar beam is small; the overwhelming majority of observations come from trains blown through the beam a significant time after they have formed.

7. Future Focus of Optical Observations

Optical observations have a continuing major role in the investigation of meteors.

The mass calibration of meteor observations is of great interest in determining real fluxes and real sizes for observed meteors. The coefficient of luminous intensity, which gives the proportion of kinetic energy of the meteoroid delivered in the optical band, is very uncertain. It depends strongly on the spectral lines present and their relative strengths, and therefore on things like collision speeds between air and meteoroid atoms, which atoms are present, and the physical and thermal properties of the meteoroid. Laboratory measurements in certain velocity ranges for certain elements have been made (Becker and Friichtenicht, 1971; Boitnott and Savage, 1971), but there is still much uncertainty. Spectral observations have much to offer in this area, as do investigations of light curve shapes, meteor begin and end heights, laboratory measurements, and, potentially, artificial meteors. Optical observations combined with measurements from other techniques (like radar or infrasound) may also help constrain the value for luminous efficiency. This will allow video systems to produce accurate fluxes.

Widespread, multistation video observations will also allow orbital distributions to be determined.

Many molecules and atoms of particular interest (carbon being an important example) radiate much more strongly in the ultraviolet and infrared regions than in the visible. In order to determine the relative abundance of these materials, other lines must be measured. The atmosphere interferes strongly with both the UV and IR regions, so the best hope for data in this area may be from cameras mounted on airplanes (on a temporary basis) or more permanently on space platforms. Carbary et al. (2004) report on one meteor observed in the UV from space, and the luminosity in this spectral region is significant.

The discussion of streams of large material capable of producing meteorites has most recently been energized by the fall of the Neuschwanstein meteorite, the orbit of which matched the Příbram meteorite (Spurný et al., 2003). While the two meteorites are chemically quite different, raising the question of whether they are truly related, the area remains a topic of significant interest. As the catalogues of bright fireball orbits increase, it will become easier to identify any streams of material which may potentially drop meteorites.

All observing methods suffer biases, including optical techniques and radar. By observing the same populations with several methods (video and radar, for example) the biases of each method can be examined, and more accurate fluxes of sporadic and shower meteors can be obtained. Simultaneous observations of brighter meteors have been made with visual and radar techniques (see Saidov and Šimek, 1989, for example), but observations of fainter meteors are needed.

Bright fireballs, particularly Geminids, have been observed to ‘flicker’; see, for example, Beech and Brown (2000) for an analysis of flickering in MORP fireballs. These rapid changes in luminosity may indicate rotation of the meteoroid. A larger sample of video and photographic light curves will allow further investigation of this phenomenon.

Some meteors, particularly in fast showers like the Leonids and Perseids, have been shown (e.g. Fujiwara et al., 1998) to have very large beginning heights, well above what might be expected from classical ablation theory. The cause of this high altitude luminosity may be airglow or sputtering of the meteoroid surface, or some unknown mechanism: further investigation is warranted. Video observations are particularly suited to this investigation, since the light at high altitudes is generally too faint for photographic systems.

Meteors have been observed on other planets; notably a fireball in Jupiter’s atmosphere observed by Voyager 1 (Cook and Duxbury, 1981). Models of ablation of meteors on other planets have been examined for Mars (Adolfsson et al., 1996), Venus (Christou, 2004) and Titan (Ip, 1990). Possible showers on Venus and visibility of meteors on Venus from Earth and from orbit were also examined by Christou and by Beech (1998).

Potential showers on Mars have been identified by Christou and Beurle (1999) and Treiman and Treiman (2000), and potential meteor shower parents have been identified for all the planets out to Saturn by Larson (2001).

The area of high-resolution studies is of particular interest, as systems become available which are capable of looking at meteors in much higher resolution than previously available. High-resolution video observations have revealed what appears to be a shock front around a meteor (Stenbaek-Nielsen and Jenniskens, 2004). Some meteors have also been found to have a diffuse or nebulous head, with significant lateral spread (Murray et al., 1999; LeBlanc et al., 2000). With small telescopes and high-resolution imagers, direct observations of fragmentation, trail width, nebulosity, and vapor caps can be made. Recent advances in tracking technology may allow very small field of view cameras to observe meteors over a significant fraction of the sky, using mirrors to direct the light to the instrument (Gural et al., 2005). All of these phenomena may reveal important processes in meteor trains measured optically and with other methods.

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METEOR44 VIDEO METEOR PHOTOMETRY

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Abstract. Meteor44 is a software system developed at MSFC for the calibration and analysis of video meteor data. The photometric range of the (8 bit) video data is extended from a visual magnitude range of from 8 to 3 to from 8 to -8 for both meteors and stellar images using saturation compensation. Camera and lens specific saturation compensation coefficients are derived from artificial variable star laboratory measurements. Saturation compensation significantly increases the number of meteors with measured intensity and improves the estimation of meteoroid mass distribution. Astrometry is automated to determine each image's plate coefficient using appropriate star catalogs. The images are simultaneously intensity calibrated from the contained stars to determine the photon sensitivity and the saturation level referenced above the atmosphere. The camera's spectral response is used to compensate for stellar color index and typical meteor spectra in order to report meteor light curves in traditional visual magnitude units. Recent efforts include improved camera calibration procedures and long focal length "streak" meteor photometry. Meteor44 has been used to analyze data from the 2001, 2002 and 2003 MSFC Leonid observational campaigns as well as several lesser showers.

Keywords: Meteor, video photometry, leonids, video calibration

1. Introduction: Why Video Meteor Photometry?

The motivation behind this work is to minimize the risk to existing and proposed space assets by the estimation of space environment conditions and effects. Meteor storms are a significant risk to operational satellites. Since mitigation measures imply down time, accurate prediction saves operators money. Our goal for video meteor photometry is to acquire and analyze video meteor observations with the intent to determine rates and population indices, which can then be used to constrain the stream models that form the basis of activity forecasts. The demand for such forecasts is significant: over 40 satellites requested predictions for the 2001 Leonid meteor storm.

Accurate photometry is needed to determine mass flux spectrum within the meteor stream for spacecraft hazard determination. In the past we have used the MeteorScan (Gural, 1995) program for intensified video meteor analysis and have found it very good for meteor detections but weak on photometry due to saturation effects. Saturation of the meteor images introduces serious non-linearity that has in the past limited the video photometry dynamic range: most bright meteors are saturated. Lens falloff, spatial and temporal sky background variations and sky transparency are also calibration concerns. Furthermore, comparisons between visual observations and GENII and GENIII intensifier observations are difficult at best due to the lack of instrument spectral response compensation. To overcome these obstacles, "Meteor44" was written to make use of on-sky flat-fields, stellar intensity and astrometry calibrations, meteor spectra, and camera/lens specific saturation compensation to improve meteor photometry.

2. Meteor44 System Overview

Meteor44 was initially conceived as a photometric program to follow MeteorScan. Although direct to disk data gathering is possible, the meteor video is usually recorded on tape as shown in Figure 1a and only later converted to AVI files for processing by MeteorScan and Meteor44. The

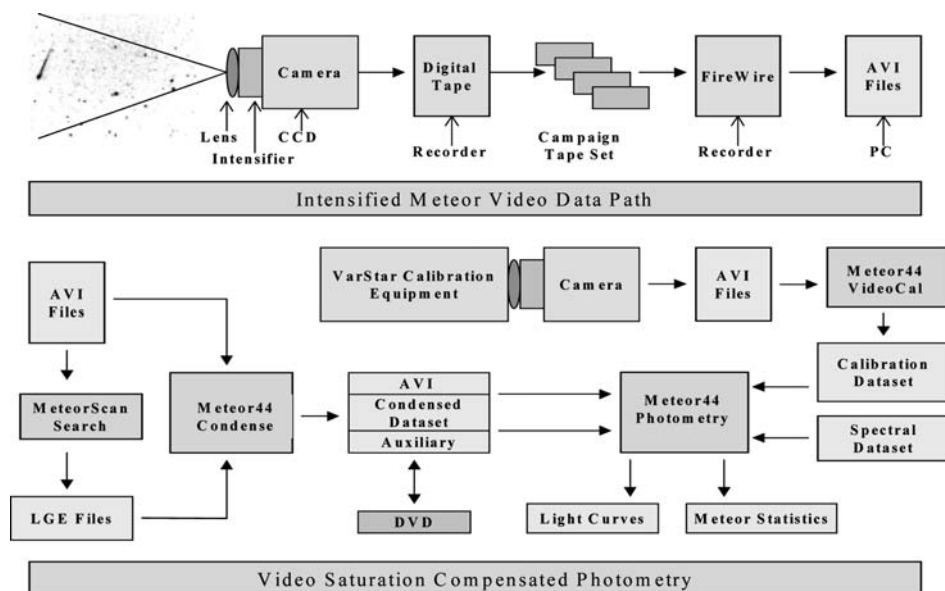


Figure 1. (a) Intensified meteor video data path from the sky to the PC. (b) Data flow for saturation compensated video photometry with artificial variable star (VarStar) calibration.

edited output log (LGE file) from MeteorScan and the AVI files are the input to Meteor44.

As shown in Figure 1b, Meteor44 is comprised of three main components: (1) “Condense” drastically reduces the size of the video data by removing frames with no meteor activity while retaining the auxiliary data. (2) “Photometry” produces calibrated meteor light curves with associated astrometric data and (3) “VideoCal” provides instrument specific saturation compensation. These components are supplemented with numerous utilities for viewing, plotting, sorting, browsing, and quality controlling the video and meteor data. The software is written in IDL, the Interactive Data Language by Research Systems, Inc. By structuring the program as an interactive graphical user interface (GUI), one is able to connect multiple data handling, analysis and visualization tools in a powerful, intuitive format. The lack of native IDL video read procedures required the development of an external C++ based dynamic link library module (avi.dll) to read Microsoft Audio Video Interface (AVI) files. Simple IDL procedures call the avi.dll in order to read and write individual frames of the video data. The shareware frame server AviSynth from sourceforge.net is used to handle the many mutant digital formats. The combination works extremely well together and allows one to play the video or view and process individual frames from within IDL without requiring vast computer resources. The program is called “Meteor44” to reflect its origin within the ED44 group of the Engineering Directorate of NASA’s Marshall Space Flight Center.

3. Meteor44 Sky glow Derived Flatfield and Background

Meteor44 automatically derives a flatfield from the sky glow, which is assumed flat. This is a reasonable assumption for moderate fields of view (FOV) more than 20° above the horizon after astronomical twilight. Most observations are made under these conditions and a single flatfield can be used for a complete night’s observations. The procedure averages several frames of meteor-free sky data, removes the stars and small-scale variations by median filtering with a 50×50 pixel box and smoothes the result. This result is normalized to unity in the center, bounded and inverted to yield a normalized, multiplying flatfield. In most cases, the flatfield produced is consistent with the classic $1/\cos^4$ curve of a widefield lens (Kingslake, 1989). Note that the compensation in the useful portion near the edge of the image approaches a factor of 2 or $\Delta m_v = 0.75$ relative to the center.

A related method is used to subtract the airglow background from the data. The stars and meteors are removed from an image as above and this background is subtracted. In practice, radial aperture photometry, described below, reduces the need for whole-image background subtraction since it

accounts for changes in local background conditions. In Meteor44 the subtraction of the sky background is used primarily to improve the ability of automated object location algorithms to locate dim stars.

4. Meteor44 Stellar Photometry and Astrometry

Radial aperture photometry (RAP), an automated form of circular aperture photometry, is used in Meteor44. RAP optimizes the target and background aperture radii based on image measurements. The mean intensity in each pixel wide ring about the centroid of the target object is determined and from this a radial point spread function and photometric curve of growth (Berry and Burnell, 2000) are calculated. From the curve of growth appropriate target and background radii are determined and target and background intensities are calculated as with traditional circular aperture photometry. The local background is determined using a robust Mean–Median–Half technique (Berry and Burnell, 2000) to avoid artifacts in crowded regions. The technique has been further adapted to meteor intensity measurements by adding an algorithm to estimate the meteor trail length to width ratio as discussed in Section 7.

The star catalog used by Meteor44 is the Sky2000 catalog, compiled by Goddard Space Flight Center for attitude determination star trackers. This catalog is an improvement over earlier general catalogs in that the m_B and m_V magnitudes are far more complete and accurate, the astrometry has been updated and selected m_R and m_I magnitudes are available as well. This is important since the GENIII detectors often chosen for meteor work are very sensitive in the near infrared. Color information from stars in the Landolt selected area catalog [Landolt, 1992] was used to perform a statistical regression relating V–R and V–I to B–V in order to estimate missing red and infrared magnitudes as suggested by Holtzman (Private communication).

To initialize the astrometry, the user clicks on 4 or 5 corresponding stars in both the sky image and a catalog image so a plate solution can be computed. Using the plate solution and catalog, Meteor44 automatically locates approximately 15 stars, applies RAP and determines their instrument response. Much of the automated astrometry in Meteor44 is adapted from previous instrument pointing programs (Dietz et al. 2002) developed for NASA. Spectral and saturation compensation are used as discussed in Sections 5 and 6 below to refine the instrument calibrations.

5. Stellar and Meteoric Spectral Response

Photometric calibration from the stars in the video images is wavelength sensitive. For simplicity, the process is broken into two parts by the

determination of the instrument magnitude, M_G based upon the photon response of the instrument. One convolves a standard spectrum of Vega, (Colina et al. 1996) the standard star, Figure 2a, and the quantum efficiency (QE) spectrum of the video detector, Figure 2b, to get $M_G = 0$ instrument response in photon units. The magnitude and color information of catalog stars in the field of view is used to estimate their spectra, which is compared to the measured instrument photon response to get a calibration in terms of instrument units and the stellar saturation threshold, *Sat*. The meteor instrument response in each field is converted into M_G , and these are combined to form the meteor light curve. Compensation (Sections 6 and 7) is applied as required.

To compare M_G photometric results to visual observations or to compare with results from another instrument requires conversion to equivalent visual magnitude, M_V . Establishing the relationship between meteoric M_G and M_V requires a knowledge of the meteor spectrum, Figure 2b, the instrument QE curve and the V-filter (Landolt, 1992) spectrum, Figure 2a. The ratio of the meteor spectrum convolved with the QE to the meteor spectrum convolved with the V-filter curve is used to estimate the M_G to M_V offset. This offset added to the meteor light curve in M_G yields the light curve in M_V and the peak value for comparison to visual estimates.

6. Saturation Compensation from “Artificial Variable Star”

Hardware and software were devised in order to determine the unique saturation compensation for each camera/lens set. The theory and construction

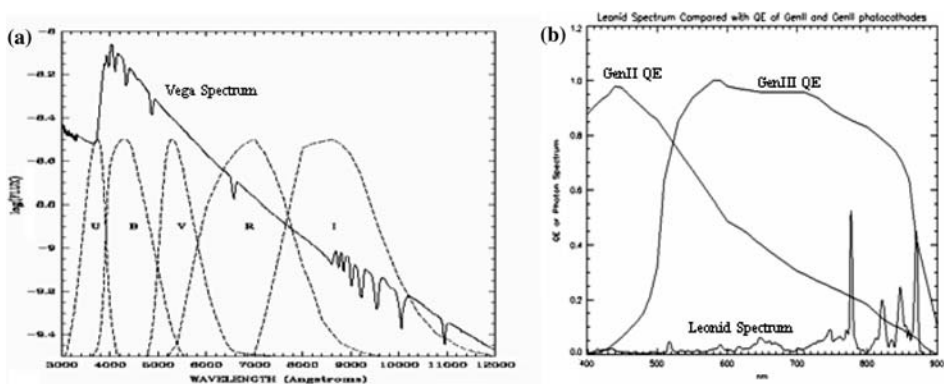


Figure 2. (a) The Vega spectrum compared with the bandpass of UBVRI filters used by Landolt. (b) The quantum efficiency (QE) spectrum of GENII and GENIII intensified video detectors compared with a sample Leonid spectrum. The response to the bright IR lines is quite different.

of “artificial variable star” video calibration hardware is fairly straightforward. Light through a rotating circular ND filter varying in intensity by 1000:1 over a two second period is focused upon a pinhole. Light from the pinhole is collimated by a telescope and is observed by the camera under test as a variable star at infinity (varstar). Neutral density filters are used to adjust the intensity so that the recorded image ranges from dim to extremely saturated. Five or ten cycles of data are recorded and processed in the same manner as meteor data.

The varstar in each field of the data is measured using RAP and correlated with filter wheel position. The power law coefficients that fit the saturated data to the filter wheel curve comprise the saturation calibration for this camera-lens combination. Although other saturation calibration function fits may be used, the best results are usually found using geometric (power law) fitting of the data to the wheel. For poorly focused systems the saturation calibration exponent can approach unity (i.e. linear) but the usual range of the calibration exponent for intensified cameras with sharp lenses is from 1.2 to 1.5. The slope of the compensation is used to estimate errors.

7. Motion Compensation: Comparing Stellar and Meteoric Images

The first thing one notices about the image of a meteor in a video frame is that the meteor has a “finger like” appearance resulting from the two fields being exposed at different times. Meteor44 handles this by separating the fields and interpolating to replace the lost lines while restoring the plate scale. The fields are then processed as if complete frames with twice as many determinations per second.

Motion of the meteor across the CCD spreads the intensity thinner than for a stellar source. This has a significant effect on the saturation threshold and the saturation compensation for the meteor. One can analyze a smeared meteor track as a translated PSF mid-section with a half PSF section on each end, as shown in Figure 3. The plateau represents the saturated region. The PSF, saturated area and the length to width ratio, L/W , are sufficient to describe the figure. For a stellar image, there is no mid section and the ratio is unity. For a meteor, the ratio depends on PSF width and the movement of the meteor during the exposure. For extremely bright meteors the broad base of the PSF is significant and the ratio approaches unity.

L and W are found from the saturated spot by examining the spot’s radial intensity function within the RAP procedure: all pixels are saturated up to radius W and no pixels are saturated beyond radius L . If one defines the stellar saturation threshold, Sat , as the minimum total intensity which will produce four saturated pixels, then one can scale this threshold for a star to

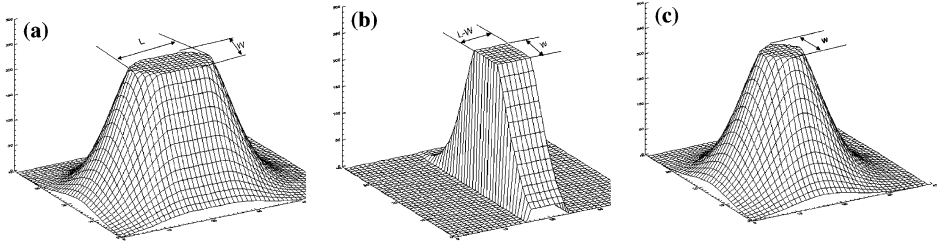


Figure 3. The saturated meteor streak exposure, (a) is the convolution of the PSF with a line but geometrically can be thought of as composed of a translated PSF, (b) and a stellar PSF portion, (c) The PSF, the saturated area and the L/W ratio are sufficient to describe the figure.

that of meteor, Sat_m as a function of L/W based on the ratio of geometric areas, $A_{\text{meteor}}/A_{\text{spot}}$.

The final meteor saturation compensation step is to apply the power law saturation technique from Section 6 for stellar images replacing Sat with Sat_m as the saturation level. Below an integrated meteor intensity of Sat_m meteor saturation compensation is not required. Above an integrated meteor intensity of Sat_m , the camera saturation compensation is determined by artificial variable star methods.

8. In Summary: An Application to the Bright 2001 Leonids

The 2001 Leonid meteor storm over North America was characterized by an extraordinary number of very bright meteors with fewer dim meteors than

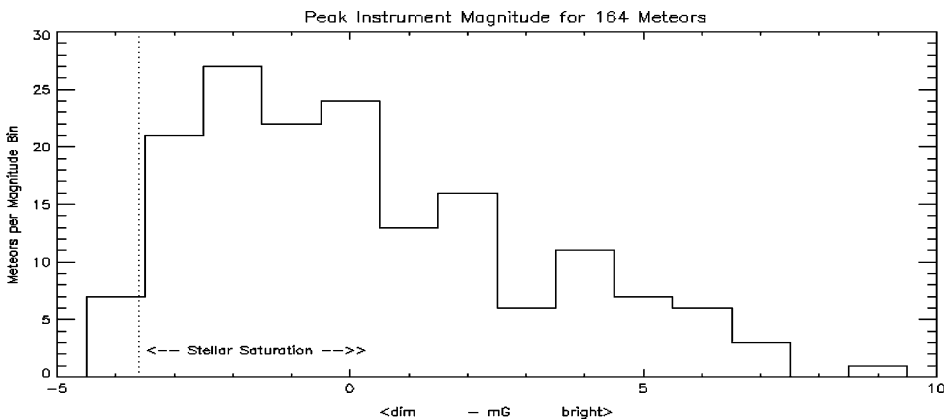


Figure 4. One hour of intensified video Leonids from Hawaii, November 18, 2001. This was old stream material with few dim meteors even though the detection limit was eight magnitude. Almost all these meteors were saturated and compensation essential. Here $M_v = M_G + 1.68$.

expected. Analysis of the intensified video data from this meteor storm provided both the motivation and the prototype for the development of these procedures: almost all meteors were very saturated (Figure 4) and there would have been little usable data if the saturated meteors had been discarded. A detailed NASA Technical Memorandum on this topic is under development.

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RESULTS FROM THE AIM-IT METEOR TRACKING SYSTEM

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Abstract. The recent development and data collection results of the Astrobiology Instrumentation for Meteor Imaging and Tracking (AIM-IT) system, has demonstrated an ability to point narrow field-of-view instruments at transient events such as meteors. AIM-IT uses the principle of tracking moving objects via a paired set of relay mirrors along with an integrated hardware/software solution, to acquire and track meteors in real-time. Development of the instrument has progressed from a prototype rocker-box system through more recent use of a fast response mirror system during several meteor shower campaigns. Several narrow field of view instruments have been deployed using AIM-IT including high spatial resolution video, high frame rate video, and meteor spectrographic equipment. Analysis of the imagery shows evidence for meteor fragmentation in as many as 20% of the meteors tracked thus far. The success of the AIM-IT technology in tracking meteors during their luminous flight provides a new tool in enhancing the capabilities and data volume that can be obtained with existing narrow field of view instruments.

Keywords: Meteor, meteor instrumentation, meteor tracking, meteor imaging, meteor spectroscopy

1. Introduction

The analysis and understanding of meteor stream orbits, dynamics, composition, and ablation physics has very often come from the application of narrow field of view instrumentation to meteor observations. These include high spatial resolution cameras for meteoroid orbital parameter estimation and stream evolution studies, high frame rate imaging for light curve analysis and ablation structure, and high resolution slit spectroscopy for composition and thermal studies. The issue that arises is that the probability a meteor will pass within a narrow field of view instrument is extremely low and thus long-term observational periods are required and the quantity of collected data is low. Recent airborne campaigns during the Leonid meteor storms of 1999,

2001, and 2002 (Jenniskens et al., 2000; Jenniskens 2002; Jenniskens and Russell 2003) attempted to take advantage of high meteor flux rates to increase the volume of data collected from a variety of instruments. However, meteor storms are rare events and an innovative means to enhance the collection rate from a given instrument is required to help answer questions in meteor astronomy.

One solution is to physically point an instrument towards a meteor to obtain the necessary information. Most instruments of interest however possess high inertia and thus make it extremely difficult to reposition them on the time scales of tenths of seconds – the typical luminous duration of an ablating meteor. An alternative solution is to steer the light from the meteor via a set of relay mirrors to a stationary instrument, thus lowering the inertial mass that must be repositioned. This concept requires very high-speed hardware and software to successfully acquire and track meteors on very short time scales. Through recent developments, these technologies are now available with the use of state-of-the-art galvanometer motors and advances in automated video meteor detection.

Such a rapid response instrument was developed under NASA's Astrobiology program element to help answer questions about meteors and their pre-biotic contributions to Earth's early development and thus the instrument was named Astrobiology Instrumentation for Meteor Imaging and Tracking (AIM-IT). The name is a slight misnomer however in that the AIM-IT system can be used to study much more than astrobiology issues in meteor astronomy.

2. Instrument Description

The AIM-IT system consists of a set of integrated hardware components and high-speed detection software for rapid meteor acquisition and tracking. The core of the hardware is a pair of Cambridge Technologies 6900 galvanometers with mirrors configured to steer anywhere within a $40^\circ \times 40^\circ$ patch of sky and provide a minimum of 50 mm clear aperture for a stationary mounted narrow field instrument. The mirrors are moved by commands from a laptop computer through a digital I/O board interfaced to a pair of motor controllers as functionally illustrated in Figure 1.

The system achieves a total repositioning and vibration settling time of 10 ms when commanded to move $\pm 20^\circ$ and requires only 2 ms for 1° shifts. This is much less than the single-field frame-time of 16 ms in standard NTSC video and the 200 ms duration of a typical meteor. To direct the mirror positioning, the meteor must be acquired and tracked in a wide field video camera that covers the entire observable area of the mirror system. Intensified video cameras with a 40° field of view are typically used in meteor

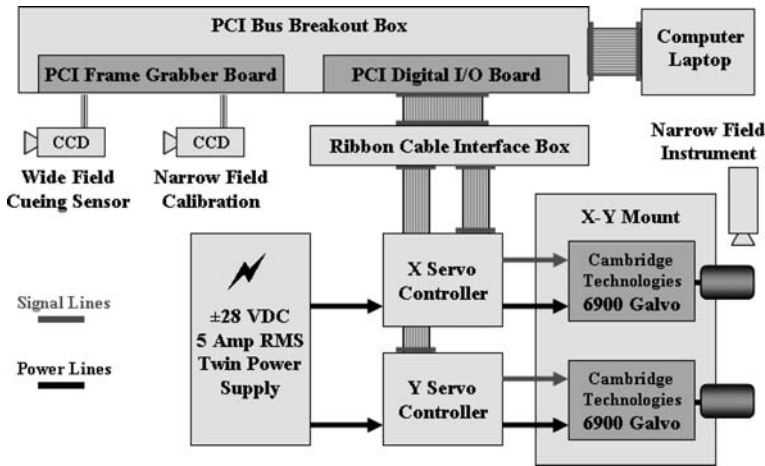


Figure 1. Block diagram of the AIM-IT system equipment interfaces.

astronomy and form the basis of the “cueing” imager for AIM-IT. The mirrors are steered towards the cue (meteor track) to relay the emitted light towards a narrow field of view instrument of the researcher’s choice. For example, a picture illustrating the equipment setup during the 2003 Leonids, using a high frame rate camera as the narrow field instrument, is depicted in Figure 2.

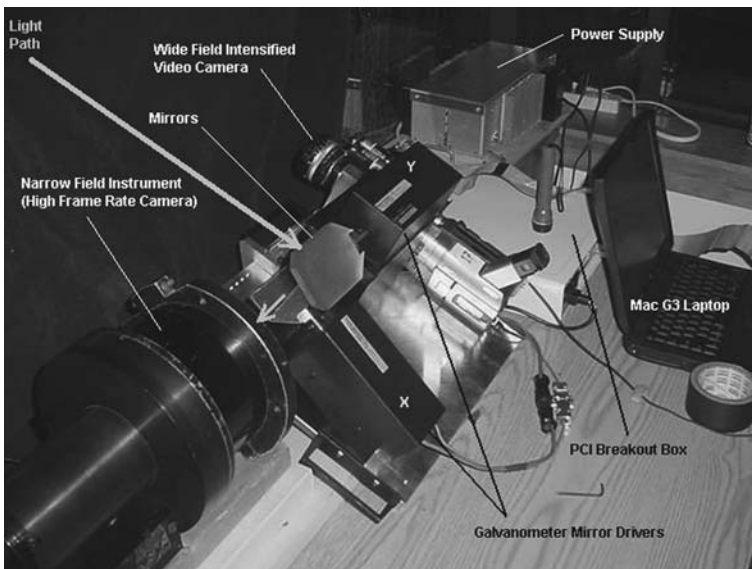


Figure 2. AIM-IT system configuration showing wide field cueing camera and mirror relay coupled to a narrow field of view instrument (high frame rate camera).

3. Image Processing

A laptop computer processes the wide field video after image capture by a LG-3 frame grabber commercially available from Scion Corporation. The LG-3 permits asynchronous image processing of previously digitized frames while grabbing the next available frame into memory on a Macintosh computer. Each digitized frame is examined for evidence of a meteor using a variant of the MeteorScan automated meteor detection software developed by one of the authors (Gural, 1999). MeteorScan's near noise limit sensitivity utilized a Hough transform/matched filter detector that contained a half second latency – a delay that would be unacceptable in the current application. Thus a re-engineered software package named MeteorCue was developed specifically for AIM-IT that employs a high speed, very low latency meteor detection algorithm that trades off some magnitude sensitivity for rapid acquisition. The current MeteorCue software detects magnitude +4 meteors in +7 stellar limiting magnitude imagery. This was deemed acceptable since the narrow field instruments to be used with AIM-IT, such as slit spectrometers, would require meteors of at least second magnitude brightness to reach sufficient signal-to-noise ratios in their sensors.

The software algorithm used for acquiring meteors is based on a custom-designed cluster detection method. The image frames are continuously passed through a first order response filter to obtain the image mean and standard deviation on a pixel-by-pixel basis. Each new frame that is digitized is then thresholded with respect to the mean image plus a user factor times the standard deviation. The exceedances are flagged and passed through a highly efficient cluster detector. The clustering algorithm involves counting the number of exceedances within 32×32 pixel accumulator cells spread across the 480×640 pixel wide field camera image. The cell dimension was based on the maximum meteor angular rate of 28 pixels per frame expected for non-hyperbolic meteors and the wide field sensor resolution of 3.75 arc minutes. Finally summed 2×2 (50% overlapping) super-cell counts are searched for a maximum whose effective 64×64 pixel region ensures a meteor will be entirely contained within a single super-cell. A cluster is considered a valid candidate if it exceeds a super-cell count threshold.

Valid clusters have their centroids computed for both the even and odd fields separately, thus providing position measurements at an effective 60 Hz update rate (NTSC video). The positions are fed to an alpha-beta tracker that first performs an association test with any previous tracks and then either initializes a new track or updates a currently active track. If there is an active track, the meteor's position is predicted ahead to the next measurement (digitizing frame) time and the pixel coordinates in the wide field coordinate system are computed. These are converted to mirror angles via a

set of closed form transformation equations whose coefficients were determined in an earlier calibration stage. The current latency of MeteorCue on a 300 MHz Macintosh G3 laptop is only 100 ms from first appearance of the meteor in the wide field camera to tracking the meteor in the narrow field instrument. Further work using odd and even row fields rather than full image frames at both the threshold and cluster stages should reduce this latency to 60 ms.

A calibration is performed to tie wide field camera pixels to mirror angles by selecting a star in the wide field and adjusting the mirrors until the same star is centered in the narrow field. For 40° fields of view the relationship can be restricted to linear plate coefficients and transformations via standard coordinates. Several stars are selected across the wide field and a least squares fit is made to determine the plate constants. As long as the wide field camera is kept rigidly fixed with respect to the mirror system, this calibration will remain valid even if the entire instrument setup is repositioned. That is, it is not necessary to re-calibrate the mirror angle transform coefficients when a different overall system orientation is chosen or a different star field is present. This makes the AIM-IT system amenable for use on a moving inertial platform such as an aircraft with continuous attitude changes.

4. Development and Design Trades

During the development of the instrument, the AIM-IT system evolved through various configurations. The initial prototype was based on a rocker box approach that physically moved a lightweight imager via two orthogonally mounted stepper motors. This provided the initial proof of concept and was flown during the Leonid Mac mission of 2002 (Jenniskens, 2002). A comparison of the design choices in the AIM-IT system is shown in Table I where the rocker box capabilities are compared to the mirror based approaches. Clearly trades can be made for cost, response time, instrumentation weight, clear aperture, and field of view coverage. Stepper motors with mirrors yield a low cost solution for long duration meteors and fireballs allowing the use of high spatial resolution video for orbital element estimation. Such a system can rival photographic resolution and enlarge the two-station viewing volume ten-fold relative to a single pair of 40° intensified video cameras. The galvanometer system with mirrors provide very accurate pointing for slit spectroscopy and high frame rate video and the fast response needed to image more typical meteors that are fainter and shorter duration. Note that the costs include a computer and all sensors required with the implication that there is an intermediate level of design that falls between the two cost extremes shown.

TABLE I
Comparison of system capabilities for various AIM-IT design options

Design feature	Stepper motor rocker box	Stepper motors with mirrors	Galvanometers with mirrors
Wide-field sensor	Intensified CCD	Intensified CCD	Intensified CCD
Wide field of view	Up to all-sky	$70^\circ \times 70^\circ$	$40^\circ \times 40^\circ$
Narrow-field sensor	Small/light <0.5 kg	Moderate size/heavy	Moderate size/Heavy
Aperture limitation	None	35 mm	50 mm
Maximum slew rate	$150^\circ/\text{s}$	$800^\circ/\text{s}$	$2000^\circ/\text{s}$
Max time to meteor	250 ms	50 ms	10 ms
Pointing resolution	1.8°	1.8°	2 arc seconds
Applications	Fireball tracker high-res trains	Video triangulation orbital elements	High-res spectroscopy high frame rate video
Cost (\$US)	\$2500	\$2500	\$17500

5. Narrow Field Imaging

The prototype rocker box system was flown on NASA's DC-8 Airborne Laboratory during the Leonid Mac mission of 2002 to monitor the Leonid meteor storm. Although far slower to respond than the galvanometer system under development at the time, the rocker box system provided validation of the basic AIM-IT concept by acquiring 380 meteors in the wide field camera and tracking 180 meteors in the narrow field imager. In particular, it acquired and tracked a magnitude -8 fireball that was a highlight of the entire mission (Jenniskens, 2002).

The galvanometer-based system with mirrors was ready for initial trials the following summer of 2003. Unfortunately, poor weather put a hold on "first light" for three weeks. Finally, on August 12, 2003 at 8:28 UT in Sterling, Virginia, USA, the first meteor tracked was a magnitude $+2$ Perseid with six more meteors obtained in two hours of observations. Further tests were then relocated to Freemont Peak Observatory, California where eight hours of observations yielded 75 meteors on the nights of August 26 and 30, 2003. This was followed by an observing run again at Freemont Peak where 33 meteors were tracked when the Orionids were active covering one and one-half hours of observations. An interesting result of some of the early observations that employed a CCD video camera for the narrow field of view sensor, has been that about 20% of the meteors imaged show twin illumination centers just prior to fade out as illustrated in Figure 3. Note that this result is from a sample taken near the times of major meteor showers without each meteor having been associated to an active radiant and therefore the

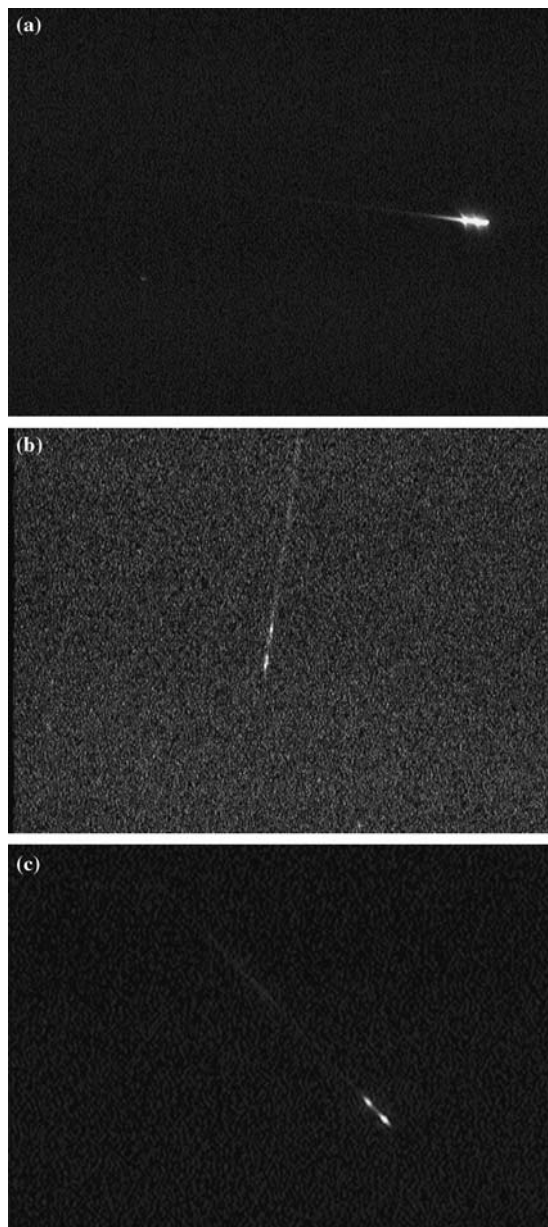


Figure 3. Examples of fragmented meteors captured in a narrow field of view imager.

20% fragmentation rate should not be generalized to all meteors or any particular shower stream at this time.

Nonetheless it is intriguing evidence for meteor fragmentation during ablation. Note that we have ruled out both multiple reflections in the mirrors

(these are first surface mirrors) and lens reflections since the paired light peaks are typically of equal intensity and don't appear in earlier and brighter portions of the meteor video record. Thus, the ability to image meteors with high spatial resolution has provided additional evidence for fragmentation in a variety of shower streams other than the Leonids. Further statistical evidence will need to be accumulated to more accurately comment on the fragility of meteors associated with other streams and sporadics.

In general, the initial tests were successful and work was begun on interfacing a spectrometer to the output of the mirror light path. This latter part has encountered difficulties in obtaining sufficient intensity of a light source on the slit of the spectrograph. A mirror pointing bias correction needed to be introduced to account for the off-axis position of the slit relative to the nominal light path. An alternative fiber-optic coupling approach was also tried to permit the spectrometer and a small CCD imager to share the narrow field of view opening. This configuration has required significant rework to improve the optical train characteristics and performance of the combined sensors. These interface problems have now been worked out and the first spectrum was obtained for the AIM-IT system in July 2004 when it successfully tracked and recorded the aircraft landing lights of a passing aircraft. First meteor spectra are expected during the fall of 2004.

6. High Frame Rate Imaging

During the Leonids meteor shower of November 2003, the AIM-IT galvanometer/mirror system was deployed at Poker Flat Research Range near Fairbanks, Alaska. This campaign was specifically aimed at obtaining high frame rate imagery of meteors using a 1000 frame per second (fps) camera developed by Hans Staebek-Nielsen of the University of Alaska. The goal was to obtain both high spatial and high temporal resolution imagery of fireball shocks as first reported in (Jenniskens and Russell, 2003).

Several issues arose during the campaign associated with the detection aspects of the AIM-IT MeteorCue software. The overall system detection sensitivity was seriously reduced due to extremely strong aurora activity that produced a rapidly changing background and large false alarm rate in the wide field sensing system. Necessarily the thresholds for detection needed to be raised thus lowering the probability of detection. Unfortunately the Leonid shower was dominated by a faint meteor component this particular epoch and thus the number of meteors acquired was significantly less than expected. In total, only eight meteors were both tracked by the AIM-IT system and were of sufficient brightness to be recorded by the 1000 fps camera. An issue involving a 10 Hz background variability from the wide field intensifier, that created a further loss in sensitivity, has since been

resolved. In addition, a mirror angle drift with pointing angle was discovered that was not significant enough to cause a problem due to the available 6° field of view in the high frame rate camera. The drifting issue was later resolved by deriving a more exact closed form solution to the mirror angle transformations.

Three interesting results arose from the high frame-rate imagery of the meteors. The first involves a 162 and 172 Hz periodicity evident in the light curve of one of the meteors. Initial analysis indicates that it was caused by the meteor crossing in and out of the inter-pixel spacing of the high frame rate camera system. The camera's CCD chip has only an 84% fill factor, thus a moving steady light source displays a sensor induced flickering of the light curve. There remains however an unaccounted for 90 Hz oscillation in the light curve of the meteor that does not appear when modeling the actual meteor track on the CCD with inter-pixel voids and appropriate point spread function. Scintillation was ruled out as well since a simultaneously imaged star only shows significant spectral energy below 50 Hz with a flat response above that frequency. Possible explanations for the 90 Hz component are only conjecture and include the possibility of a rapidly rotating meteoroid or a periodic wake instability manifesting itself in a pulsating light curve. Further testing of the imaging system is required however, to rule out any sensor-based causes for the periodicity seen. The second interesting feature was that several meteors were saturated in the high frame rate camera while staring (mirrors motionless), but became unsaturated when the mirrors moved every 33 ms and the meteor smeared across the CCD by several pixels. When the integrated counts from all pixels containing the meteor were added, the smeared meteor frames had anywhere from the same number to twice the counts of the saturated frames. This evidence demonstrates the non-linear response of CCDs when in saturation and that not all the energy on a saturated pixel bleeds over to adjacent pixel sites. Thus careful consideration must be taken when calibrating meteor light curves for those meteors that are bright enough to be saturated on a CCD.

The last result involves a magnitude -1 meteor that fragmented into two pieces during one of the longer (0.75 s) high frame rate collections. In Figure 4 are shown the frames from 0.2, 0.4, and 0.5 s relative to the start of initial tracking. The meteor is clearly split into two parts during its ablation. Based on the relative angle rate of the diverging pieces, the meteor fragmented approximately one-tenth second before maximum brightness. There is no evidence to indicate this was two separate meteors that were co-aligned at one point in the trail, as the spatial spread prior to the time of fragmentation does not show any elongation or splitting of the intensity profile. Also perfect alignment of two meteors along the line of sight would be a highly improbable event. Since there were numerous frames available and the meteor is of long duration with a reference star visible in the narrow field

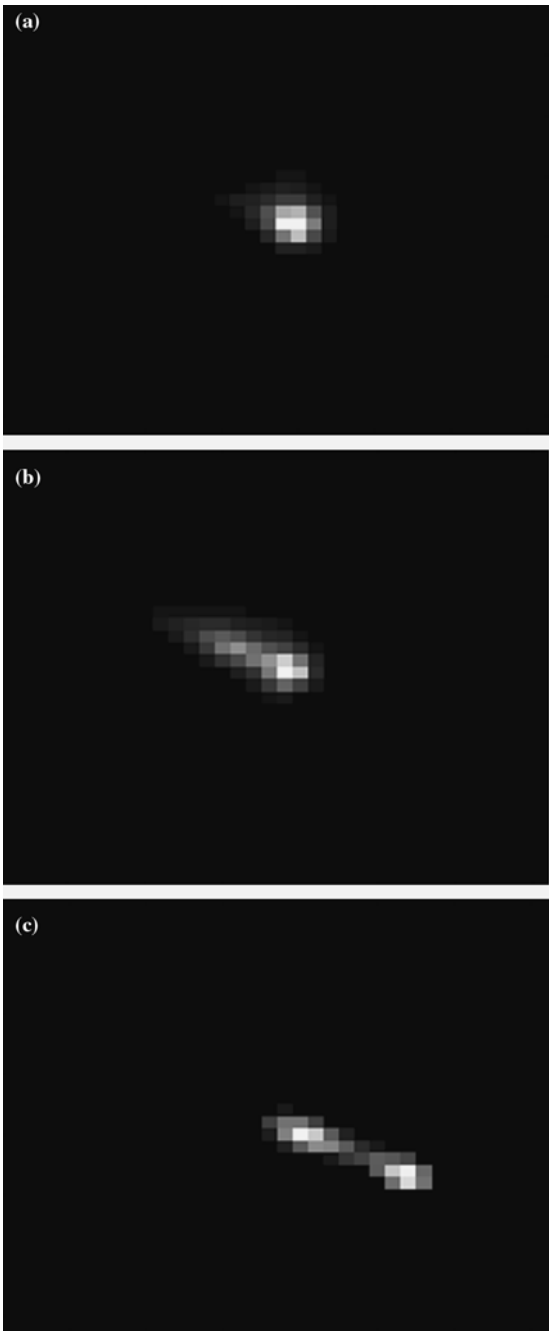


Figure 4. Selected frames of a fragmenting meteor collected with a high-speed imager on November 16, 2004 at 13:48:51 UT.

imagery, it was possible to discern not only the radiant direction but also the radiant angular distance based upon the apparent angular velocity rate of change. This latter calculation is possible from the geometric effects of angle rate change for a moderate length meteor track and was computed using the formulae published in Shiba (1995). This yielded a radiant distance for the meteor at its end height of 108° from its radiant. Attempts at association with the active meteor showers on the night of November 16 however places the meteor radiant more than 15° from the closest stream (Northern Taurids) and thus was categorized as a sporadic.

Unfortunately this classification makes it more difficult to place values on the incoming speed and distance. Note however that the nearly perpendicular motion of this meteor to the camera's line of sight (108° from radiant) permits us to place an approximate value on the relative speed between the two particles since there was negligible foreshortening effect from geometry. If one assumes the end height of this meteor to fall between 75 and 95 km, the range to the meteor is between 168 and 212 km, and the entry velocity is estimated to have fallen between 39 and 49 km/s which provided further evidence for not associating the meteor with any of the active radiants. Under these assumptions the relative speed of the two particles is between 2.0 and 2.5 km/s. This is approximately 5% of the mean angular velocity of the meteor and represents a significant change in velocity between the two pieces. Further modeling and analysis is required to understand the physics behind such dramatic acceleration changes in the flight profile due to the meteoroid's fragmentation.

7. Summary

The AIM-IT meteor tracking system has been demonstrated to provide high quality acquisition and tracking of meteors during several meteor-imaging campaigns. Through the use of a rapidly slewing mirror relay, the luminous portion of a meteor's track can be directed into a narrow field-of-view instrument within 100 ms of a meteor's first appearance. The success of the AIM-IT technology provides a new tool for meteor astronomy in enhancing the capabilities and data volume that can be obtained with existing narrow field meteor instrumentation.

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THE DEVELOPMENT OF THE SPANISH FIREBALL NETWORK USING A NEW ALL-SKY CCD SYSTEM

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Abstract. We have developed an all-sky charge coupled devices (CCD) automatic system for detecting meteors and fireballs that will be operative in four stations in Spain during 2005. The cameras were developed following the BOOTES-1 prototype installed at the El Arenosillo Observatory in 2002, which is based on a CCD detector of 4096×4096 pixels with a fish-eye lens that provides an all-sky image with enough resolution to make accurate astrometric measurements. Since late 2004, a couple of cameras at two of the four stations operate for 30 s in alternate exposures, allowing 100% time coverage. The stellar limiting magnitude of the images is $+10$ in the zenith, and $+8$ below $\sim 65^\circ$ of zenithal angle. As a result, the images provide enough comparison stars to make astrometric measurements of faint meteors and fireballs with an accuracy of ~ 2 arcminutes. Using this prototype, four automatic all-sky CCD stations have been developed, two in Andalusia and two in the Valencian Community, to start full operation of the Spanish Fireball Network. In addition to all-sky coverage, we are developing a fireball spectroscopy program using medium field lenses with additional CCD cameras. Here we present the first images obtained from the El Arenosillo and La Mayora stations in Andalusia during their first months of activity. The detection of the Jan 27, 2003 superbolide of -17 ± 1 absolute magnitude that overflowed Algeria and Morocco is an example of the detection capability of our prototype.

1. Introduction

In recent years, our team has been developing the application of charge coupled devices (CCD) cameras to new fields of research. With the increasing size of the CCD chips, we started in 2002 to consider the development of

all-sky CCD imaging in order to find alternatives to classical all-sky photography. In November 2002, the first prototype of the all-sky camera was developed by A.J. Castro-Tirado et al. (2005, submitted) in the framework of the BOOTES-1 Project at El Arenosillo Observatory located at the Atmospheric Sound Station (ESAt) and under the auspices of the *División de Ciencias del Espacio* of the *Instituto Nacional de Tecnología Aeroespacial (INTA)* (Castro-Tirado et al., 1998). The previous steps involved one year of work finding lenses compatible to the CCD camera, involving the development of new software and hardware, in order to develop a compact instrument capable of obtaining a continuous and automatic base of full coverage of the sky. As a result of this work, the all-sky CCD system presented in Castro-Tirado et al. (2005, submitted) and discussed here performed excellently. This system can be applied to several cutting-edge research fields of astrophysics although we will focus here on its capabilities to study meteors and fireballs. We also describe the current status of the Spanish Fireball Network focusing in the important role that CCD systems can play in Meteor Science.

The first two stations located in Andalusia were operative for the first time in August 2004 as they followed Perseid activity operated by members of the *Instituto de Astrofísica de Andalucía-Consejo Superior de Investigaciones Científicas (IAA-CSIC)*. Another two stations have been operative since early 2005 in the provinces of Valencia and Castelló operated by the team of the *Observatori Astronòmic de la Universitat de València*. In addition to these initial four stations, we plan to extend additional all-sky CCD cameras around Spain during the next few years. The main aim of this network is the detection of fireballs and even larger events, i.e. those with brightnesses greater than -17 visual magnitude, usually called superbolides (Ceplecha et al., 1999). The study of these impressive events is important for two main reasons. First, they are usually associated with bodies with masses larger than 1000 kg (Ceplecha, 1996; Nemtchinov et al., 1997) corresponding to a size range between 0.1 and several tens of meters (Spurny et al., 2003) that produce meteorites. Second, the impacts of these bodies on the terrestrial atmosphere can provide information on large objects that are in Earth-crossing orbits from which they are released by impact processes. Recently, there has been an increasing appreciation for the hazards posed by *Near-Earth Objects* (NEOs) whose motions can bring them into dangerous encounters with our planet. The smaller population of these bodies is formed by objects of several tens of meters in diameter whose detection is only possible by using *Spacewatch Telescopes*, when these objects are in near-Earth space (Rabinowitz et al., 1993) or by monitoring fireball activity from ground-based Fireball Networks (Nemtchinov et al., 1997; Spurny et al., 2003). The development of new systems for all-sky fireball monitoring as the one presented here can be crucial for increasing the number of recorded superbolide events.

2. Instrumentation, Data Reduction And Observation Sites

The all-sky CCD prototype consists of a CCD Apogee AP16E camera with a 16 mm Nikkon f/3.5 lens. The CCD camera has a chip Kodak KAF168001 of 4096×4096 pixels. The above-mentioned all-sky CCD system allows the coverage of a field of view of 180° in diagonal (for more details see Castro-Tirado et al. 2005, submitted). Every station has a couple of cameras in order to cover continuously the sky, avoiding the loss due to image downloading. Typical camera exposures are 30 s, a similar time that the camera takes to download an image. The system is compact and the short exposure time avoids the need of stellar tracking. In consequence the all-sky CCD camera can be brought and installed anywhere. In order for the camera to operate remotely, it is necessary for it to be installed under a small moving roof with an automatic control responsive to changing weather conditions. The images are saved on a normal PC with a moderate storage capacity. One camera produces 1.2 Gb/hour of data because every image is 33 Mb in size. In the current configuration every camera requires a computer, while the content of a night can be stored in 3 DVD.

In order to determine the velocity of the fireballs, a measurement technique is needed. During the first months the cameras have been operating without rotating shutters, but mechanical chopping wheels are being built based on the electronics and shutters developed by H. Betlem (Dutch Meteor Society) that we are currently using in our batteries of cameras (Trigo-Rodriguez et al., 2004). We do not discount the future possibility of using other methods to produce internal shuttering close to the focal plane. In the example provided here, we have made simultaneous video observations of part of the field covered by the all-sky system. Although 25 frames per second were available from the video, in the fireball example given in Section 3 we only present trajectory data because we consider that any velocity estimation made from the video camera would not be representative of the future all-sky configuration with the rotating shutter. Consequently, we will discuss the determination of orbital data and fireball dynamics in a future paper.

Table I gives the position of the four stations forming the initial nucleus of the network. Once full operation is reached, every station will have two all-sky cameras as described below. There will also be several additional instruments applied to the detection of fireballs and meteor spectroscopy. The first two stations listed in Table I are located in Andalusia; they are operated by the *Instituto de Astrofísica de Andalucía (IAA)* and *Instituto Nacional de Tecnología Aeroespacial (INTA)*. The last two stations are located in the Valencia Community and are operated by the *Observatori Astronòmic de la Universitat de València (UV)*.

TABLE I
Location of the first four stations of the Spanish Fireball Network

Station (Province)	Longitude (W)	Latitude (N)	Altitude (m)
El Arenosillo (Huelva)	06°43'58"	37°06'16"	40
La Mayora (Málaga)	04°02'40"	36°45'35"	60
Aras de los Olmos (València)	01°06'32"	39°56'56"	1300
Vistabella (Castelló)	00°15'56"	40°16'43"	1050

For more details see the text.

3. Capabilities of The System Detecting Fireballs

The application of slow-scan CCD to the detection of meteors and fireballs is a relatively new field (Taylor, 1999; von Zahn, 1999; Kruschwitz et al., 2001; Brown et al., 2002; Trigo-Rodríguez et al., 2003, 2004). The first superbolide reported using high resolution low-scan all-sky CCD imaging was the one that appeared over Algeria and Morocco on January 27th, 2003 (Trigo-Rodríguez et al., 2003). CCD imaging has important differences with other methods such as photography or video. Some of the advantages and disadvantages of all-sky CCD imaging are discussed below. We focus on system efficiency, stellar and meteor limiting magnitudes, and astrometric accuracy.

3.1. SYSTEM EFFICIENCY

The efficiency of a CCD camera is usually estimated in terms of the quantum efficiency (QE). This is a measure of how efficient a detector is in converting incident photons into a signal. CCD cameras have a higher efficiency than photographic plates, and they also cover a wider range of the electromagnetic spectrum. Photographic emulsions have a low QE, at best about 3% for astronomical emulsions. The CCD used in our prototype is able to detect photons produced in the interval of 300 to about 1050 nm; the QE is higher than 30% between 410 and 870 nm (Figure 1). This last range is a region of the electromagnetic spectrum where meteor radiation usually occurs (Borovicka, 1993).

3.2. LIMITING STELLAR AND METEOR MAGNITUDES

During dark nights our system reaches a stellar magnitude of +10 in the zenith, although below 65° of zenithal angle, it only reaches +8 stellar magnitude. Depending on the atmospheric conditions, extinction can cause

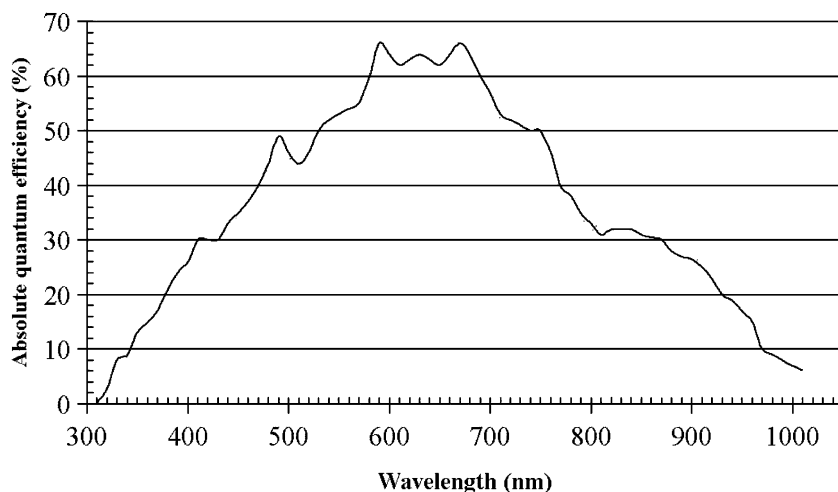


Figure 1. Quantum efficiency of the chip detector of the all-sky CCD camera prototype.

the loss of one to three magnitudes close to the horizon. Under the particular geometric conditions of observation for every meteor, their magnitude in the CCD chip will change in a similar way as happens in photography (Rendtel, 1993). The angular velocity of a meteor varies basically as a function of its geocentric velocity, the distance to the radiant and its height of appearance in the sky (Kresakova, 1969; Koschak et al., 1995). Consequently, meteors from the same shower with similar geocentric velocities exhibit different angular velocities as a function of the angular distance to the radiant and the zenithal angle of appearance. As the meteor moves faster than the stars across a number of pixels during the integration time, the magnitude of the meteor on the CCD image appears apparently fainter than it really was. Different simulations have been performed using a Monte Carlo approach (Gural, 2001) in order to determine the limiting magnitude of the system depending on the three previously mentioned variables. The simulation takes into account system losses in the magnitude of the meteor, not only as a consequence of angular velocity changes depending its position on the sky, but also as functions of meteor distance, lens vignetting and extinction. The Monte Carlo simulation propagates a random distribution of dynamically associated meteoroids in the Earth's atmosphere according to the procedure described in Gural (2001). The simulation's main output consists of plots showing the limiting magnitude contours of our system. Results are summarized in Figure 2 where the limiting magnitude of the system for two extreme cases of meteoroids with geocentric velocity of 12 and 72 km/s is given. In the plots, it is evident that the faintest meteors of a shower can be recorded close to the radiant where the angular velocity is minimized. For a low-geocentric velocity shower, the meteor limiting magnitude for nearly

stationary meteors (close to the radiant) is $+3$, while for the rest of the sky, it changes between $+2$ and -2 (this last value for an altitude of 20°). For a high-geocentric velocity stream, the contour distribution is similar but the system's efficiency decreases about 2 magnitudes.

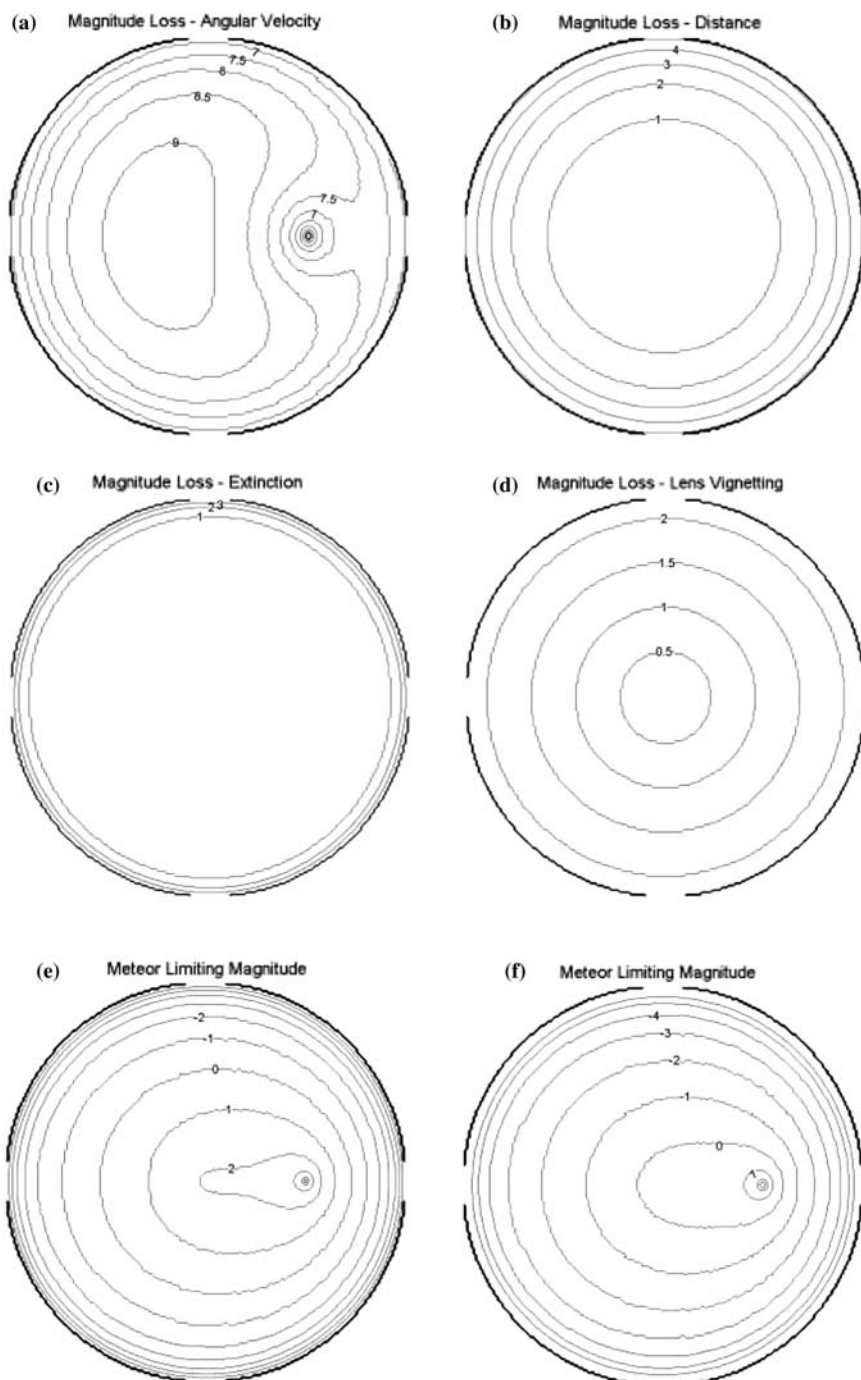
3.3. PHOTOMETRY

In order to obtain information on the mass of the incident meteoroid and compile data on the magnitude distribution in the sensitivity range imaged by the system, detailed photometry of every meteor is necessary. Unfortunately, CCD imaging of bright sources introduce blooming, or spillover of signal into nearby pixels (Hawkes, 2002). As a consequence, the peak pixel intensity is not a valid measure of the meteor brightness except for the faintest meteors. In fact, in the images, bright meteors clearly spread their brightness over several pixels (see e.g. Figure 4). In order to study the spillover of signal for bright fireballs, we have developed several methods of photometric calibration of the system. Detection of satellites typically occurs in the all-sky CCD images. Iridium satellite flares or other artificial satellites are reasonably well-predicted in luminosity, angular velocity and duration. Bright astronomical objects like planets or the Moon can be also used if we obtain calibration images of very short duration, i.e., one tenth of second or less, to simulate typical flare expositions. Another important point to be studied in the future is the necessity of defining a new magnitude system for CCD imaging systems detecting meteors. The usual panchromatic magnitude system cannot be applied to our CCD observations because the wavelength range of our all-sky CCD camera is wider than the panchromatic one (Figure 1). The future use of radiometers in our stations would allow us to obtain detailed calibration of the brightest fireball events.

3.4. ASTROMETRIC ACCURACY FROM ALL-SKY IMAGES

We are basically applying the same reduction method to CCD images that we had applied until now to photographic images. In fact, in the last

Figure 2. Monte Carlo simulations of the limiting meteor magnitude for the all-sky CCD camera. The first four figures (a to d) show the relative contribution of each magnitude loss terms: (a) Magnitude loss due to angular velocity for an entry velocity of 42 km/s; (b) Loss due to the distance of the meteors; (c) Loss due to atmospheric extinction; and (d) Loss as a consequence of lens vignetting. The resulting limiting magnitude of the system for meteors appearing from a radiant altitude of 45° is given in the last two figures for the two extreme cases of geocentric velocity: (e) 12 km/s, and (f) 72 km/s.



decade photographic negatives have been scanned in order to obtain digital images that can be studied with software similar to that used in CCD imaging. Big areas of the images surrounding the meteors are saved; this provides enough comparison stars to obtain good astrometry. We used PhotoFinish 4 software to make the astrometric measures of the star trails and the meteors. These measurements are then introduced into our *Network* software, which was used to calculate the equatorial coordinates of the meteors and the astrometric accuracy from the measured deviations of the comparison stars. This software also allows us to identify the same meteor from various stations by assuming typical values of ablation height through an automated search on the database for meteors that appeared during the same observing interval. This procedure allows a quick identification of the different meteors registered from different stations and the direct calculation of the atmospheric trajectory and radiant for each meteor. The velocity of the meteoroid is derived from the number of shutter breaks taking into account the particular geometry of the meteor in reference to the movement of the shutter. To determine orbital elements from our trajectory data we are using systematically for consistency the *MORB* program provided by Ceplecha et al. (2000) from the Ondrejov Observatory in Czech Republic. Following this procedure, we have recently published several papers on the determination of meteoroid orbits, making the astrometry of the meteors from photographs (Trigo-Rodríguez et al., 2002) or by combining CCD, video and photographic records (Trigo-Rodríguez et al., 2004).

In reference to the accuracy of the all-sky CCD system discussed here, and considering that the 4096 pixels chip covers 150° of sky, the maximum accuracy that can be reached is 2.2 arcminutes. In practice, using pixel-interpolation techniques we can improve such value (Table II). The precision of our all-sky CCD system is lower than that obtained from the all-sky photographic cameras of the European Fireball Network (typically between 0.5 and 1 arcminutes, Ceplecha et al., 1993). Probably in the near future, new CCD chips with sizes five times larger than that used in our prototype will be able to achieve the precision obtained from photographic all-sky cameras. As an example of the capability of our all-sky cameras, we show fireball SPMN030804 in Figure 3. This Perseid fireball was imaged on August 12, 2004 at 23 h 51 m 23 s UT. During those days, video records were performed in common with a Mintron 12V1C-EX based on the SONY Exview HAD ICX249AL chip with an objective with a 3.5 mm focal distance that covers a field of 86×66 square degrees. The astrometric results from both stations are shown in Tables II and III. The astrometric uncertainty of the all-sky image is 1.9 arcminutes, even better than that obtained from the video camera. Table IV compiles trajectory data obtained on this fireball.

TABLE II
Astrometric measurements of the all-sky CCD image of the SPMN030804 fireball analyzed here (Figure 2a)

SAO #	X	Y	RA	DEC	ϵ_{aver} (arcminutes)
181	1856	−1575	01 h 08 m 32 s	+ 86°13′00″	2.43
171	1907	−1553	01 h 03 m 09 s	+ 84°36′50″	0.83
106	1961	−1511	00 h 40 m 06 s	+ 82°33′00″	3.43
102	1896	−1538	00 h 37 m 12 s	+ 84°38′44″	2.27
500	2027	−1644	03 h 10 m 57 s	+ 81°29′14″	1.95
433	2030	−1622	02 h 49 m 24 s	+ 81°27′21″	3.62
345	2026	−1582	02 h 09 m 57 s	+ 81°29′58″	1.59
344	2032	−1581	02 h 09 m 46 s	+ 81°18′40″	1.20
294	2026	−1563	01 h 51 m 43 s	+ 81°22′34″	1.07
263	2021	−1553	01 h 41 m 16 s	+ 81°26′19″	1.75
291	2041	−1557	01 h 48 m 57 s	+ 80°52′31″	2.31
342	2053	−1575	02 h 06 m 54 s	+ 80°37′59″	2.43
372	2053	−1590	02 h 20 m 21 s	+ 80°42′05″	2.35
218	2030	−1526	01 h 19 m 10 s	+ 80°52′24″	0.71
162	2031	−1503	01 h 00 m 23 s	+ 80°31′09″	1.59
4331	2052	−1507	01 h 09 m 37 s	+ 79°58′39″	2.31
Averaged uncertainty (arcminutes)					1.91
Meteor position			RA	DEC	
Beg.	2084	−1569	02 h 06 m 01 s	+ 79°37′47″	
End	1918	−1548	01 h 02 m 26 s	+ 84°15′23″	

SAO # is the stellar number in the SAO Catalogue; X, Y are the apparent positions of the stars on the image; RA (right ascension) and DEC (declination) are the absolute coordinates, and ϵ_{aver} is the astrometric standard deviation. The last column gives the astrometric error of the position of every star. The last two rows on the bottom of the table give the apparent (X, Y) position of the fireball and its calculated absolute coordinates.

3.5. ADDITIONAL SPECTROSCOPIC PROGRAM

In addition to the all-sky program, the two stations of the network located in Andalusia have additional CCD ST8E cameras dotted with a f2.8/50 mm

Figure 3. −5 absolute magnitude Perseid fireball (SPMN030804) recorded at the BOOTES-2 CCD all-sky station located at La Mayora (Málaga) on August 11, 2004. The fireball appeared at 23 h 51 m 23 s UT. On the left is shown the all-sky image where the marked area is enlarged on the right (image a). The same fireball recorded at La Sagra Observatory of the Instituto de Astrofísica de Andalucía is shown on the right (image b). The astrometry of both images is given in Tables II and III. Basic data on the trajectory and radiant appear in Table IV.

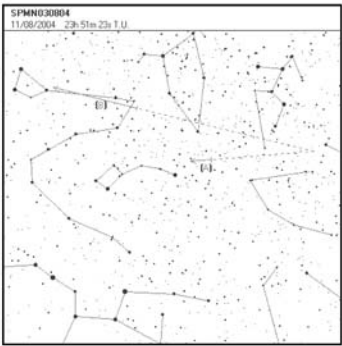
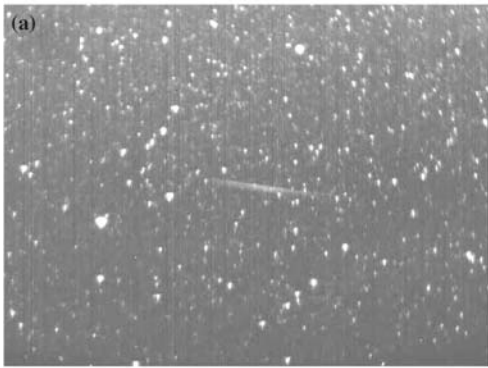
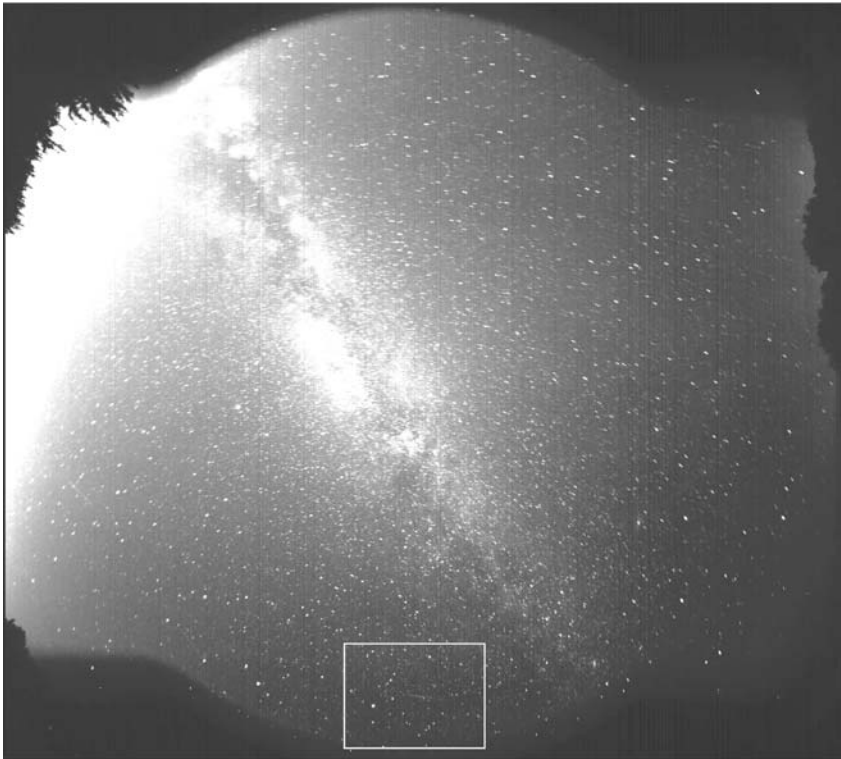


TABLE III

Astrometric measurements of the video image of the fireball (Figure 2b)

SAO #	X	Y	RA	DEC	ϵ_{aver} (arcminutes)
8890	165	−411	17 h 42 m 23 s	+ 72°08′21″	2.17
9087	218	−366	18 h 21 m 37 s	+ 72°08′21″	3.06
9366	289	−367	19 h 16 m 27 s	+ 73°18′38″	4.76
9540	319	−300	19 h 48 m 38 s	+ 70°13′56″	3.21
18396	292	−295	19 h 32 m 02 s	+ 69°40′14″	1.81
18222	251	−269	19 h 11 m 54 s	+ 67°40′54″	3.88
18299	256	−230	19 h 20 m 56 s	+ 65°41′50″	1.99
31039	108	−124	18 h 32 m 59 s	+ 57°02′49″	3.38
30949	103	−161	18 h 24 m 10 s	+ 58°47′37″	2.14
31218	163	−145	18 h 50 m 55 s	+ 59°24′40″	2.55
17828	131	−260	18 h 13 m 36 s	+ 64°24′13″	1.90
17888	161	−267	18 h 25 m 32 s	+ 65°34′23″	2.76
17365	42	−359	17 h 09 m 12 s	+ 65°41′07″	3.16
17526	106	−363	17 h 31 m 56 s	+ 68°08′37″	0.53
17576	119	−367	17 h 36 m 15 s	+ 68°45′56″	3.75
Averaged uncertainty (arcminutes)					2.74
Meteor position			RA	DEC	
Beg.	321	−329	19 h 46 m 32 s	+ 71°46′55″	
End	46	−167	18 h 02 m 22 s	+ 57°29′12″	

For more details see Table II.

TABLE IV

Basic data of SPMN030804

SPMN030804 2004 August 11, T= 23 h 51 m 23 ± 1 s UT			
Atmospheric trajectory data			
	Beginning	Max. light	Terminal
Height (km)	108.2 ± 0.6	101.2 ± 0.5	96.5 ± 0.5
Longitude (°W)	2.953 ± 0.005	3.512 ± 0.005	3.651 ± 0.005
Latitude (°N)	39.612 ± 0.004	39.070 ± 0.004	38.945 ± 0.005
Absolute magnitude	0	−5	−2
SPMN stations:	La Mayora (Malaga) and La Sagra (Granada)		
Radiant data (J2000.0)			
	Observed	Geocentric	
Right ascension (°)	44.1 ± 0.6	45.3 ± 0.6	
Declination (°)	58.2 ± 0.5	57.9 ± 0.5	

lens. Diffraction gratings of 1200 grooves/mm are placed in front of the lens in order to obtain a spectrograph with a field of $16^\circ \times 11^\circ$. On August 12, 2004 at 01 h 14 m UT we obtained from La Mayora station the first detailed meteor spectrum corresponding to a Perseid meteor (SPMN-PER01). Initial results on this spectrum that covers the range $\sim 4700\text{--}6750 \text{ \AA}$ with a resolution of $\sim 3 \text{ \AA pix}^{-1}$ have been published recently (Trigo-Rodríguez et al., 2005). We plan to do spectroscopic research from all SPMN stations once the development of the network is completed.

4. Discussion

The all-sky CCD camera system discussed here can make important contributions in several fields of meteor science. Future development of automatic detection software will allow us to obtain very reliable information on meteors in a wide magnitude range. The cameras can also be networked using an Internet connection with a low maintenance cost. The sensitivity of the system to detect meteors of limiting magnitude +1 to +3 is remarkable because it makes applicable to study elusive meteor showers. As a consequence, this all-sky CCD system can provide information on activity profiles, spatial flux densities and population index of meteor showers in a wide magnitude interval. CCD studies can be also complemented with video-techniques (Trigo-Rodríguez et al., 2004).

In relation with the detection of bright fireballs associated with meteorite dropping events, there is a renewed interest in the detection of energetic bolides that can occasionally produce meteorites. We hope that the development of our network makes it possible to recover meteorites in regions of the Iberian Peninsula and northern Africa. Both locations are very suitable for the recovery of meteorites and the following of meteorite-dropping fireball events. The efficiency of the all-sky CCD system reported here is exemplified by the detection of the January 2003 superbolide over Algeria and Morocco shown in Figure 4 (Trigo-Rodríguez et al., 2004). Although global space-based observations are very useful in estimating the real influx of interplanetary bodies that produce superbolides and the energy released in the atmosphere (Tagliaferri et al., 1994), such detectors are usually unable to provide trajectory data with sufficient accuracy to deduce the recovery area of the associated meteorites. Moreover, global space sensors have difficulty in determining the velocity of bodies entering in the atmosphere when usually their magnitude is under the detection limit. The velocity at infinity, is a key factor in determining the kinetic energy of the body at the instant of interception with the Earth; this is a key parameter for determining the orbit of the body in the solar system. All these points make it necessary to increase the area covered by

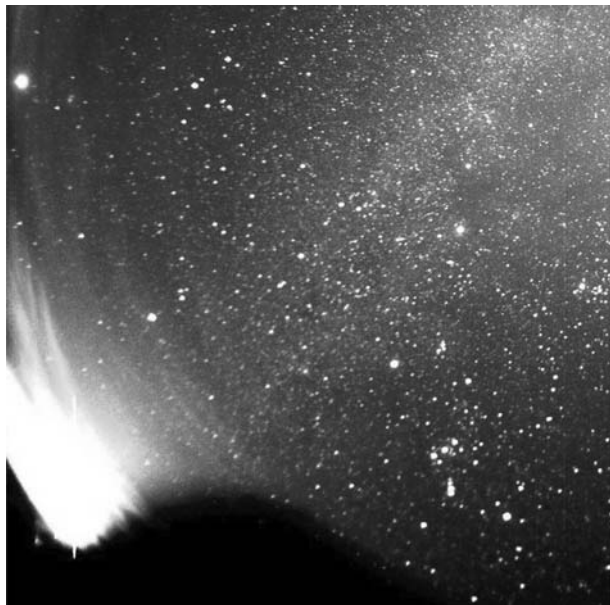


Figure 4. The 27th January 2003 superbolide of magnitude -17 detected at the BOOTES-1 station located at El Arenosillo (Mazagón, Huelva) after first light in Dec 2002, by the newly developed CCD all-sky camera. High-clouds disperse the light associated with the bright-flare, here saturated to see the stars. This observatory, located in Southern Spain, was more than 500 km away from the fireball. The true trajectory of the fireball is inclined 30° Clockwise, and it was also registered with the medium-field CCD cameras.

photographic or digital networks; this importance is enhanced by the necessity of calibrating the energy released and luminous efficiency of superbolide events (Ceplecha et al., 1998, 1999). In order to obtain substantial advances, it is crucial to obtain simultaneous recordings of superbolides from the ground and from space, making possible the calibration of these events.

5. Conclusions

In the last couple of years a new type of optical observations of meteors based in all-sky imaging has been very successful tested in Southern Spain. The first stages of the development of our network allow us to reach the following conclusions:

- (i) The all-sky CCD prototype high efficiency makes it an excellent system for following meteor showers and fireball events. The system allows automatic and remote operation, and is characterized by excellent performance and a low cost maintenance. The wide

wavelength range and high efficiency covered by the system makes it highly competitive.

- (ii) The astrometric accuracy of the system is ~ 2 arcminutes that can be improved at using pixel-interpolation techniques. Although this precision is little bit lower than that obtained with all-sky photographic cameras, it is close to previous photographic all-sky systems. Future advances in the development of large CCD chips, probably during the next decade, will make possible the development of more accurate all-sky CCD detectors.
- (iii) Although one problem of applying CCD imaging systems to study fireballs is that bright sources cause blooming of the signal into nearby pixels, the image saturation can be calibrated using easily available astronomical sources.
- (iv) The all-sky CCD system has a valuable additional utility. Its application to other fields such as GRBs, variable stars, and other elusive astronomical objects can help distribute this kind of system to other groups, as described in Castro-Tirado et al. (2005, submitted). This fact can allow the development of these low-cost maintenance systems around the world, having important implications in the development of several areas of meteor science.

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MULTI-INSTRUMENT OBSERVATIONS OF BRIGHT METEORS IN THE CZECH REPUBLIC

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Abstract. We present detailed data on 8 bright meteors recorded simultaneously by different observational techniques. All meteors were recorded by all-sky cameras at the Czech stations of the European Fireball Network and by image intensified TV cameras placed at Ondřejov and Kunzak observatories. As well as direct photographic and LLLTV recordings, most of meteors were recorded also by the spectral TV camera and some also by photographic spectral cameras. For 6 cases, lightcurves from radiometers with very high time resolution (1200 s^{-1}) are also available. From all these detections we found a significant difference between TV and photographic beginning heights. TV beginnings are in average about 40 km higher than the photographic ones. We found that meteor brightness is up to 2 magnitudes higher in the photographic system than in the TV system. This difference for high velocity meteors is mainly caused by the presence of strong Ca^+ lines in the blue part of the spectrum, where the image intensifier is only marginally sensitive. At heights above 110 km, the Na line is usually brighter than the Mg line, while at lower heights both lines have comparable brightness. In one of two captured spectra of short duration luminous trains, a small initial brightening of the Mg and Na lines caused by recombination processes was observed.

1. Observational Data

All 8 meteors presented here were observed in the scope of regular photographic monitoring of fireballs in the Czech part of the European Fireball Network and simultaneously by sensitive LLLTV cameras, which were operated during summer campaigns at Ondřejov and Kunzak observatories. Photographic observations were carried out by all-sky cameras equipped with very precise fish-eye lenses (Zeiss Distagon 3.5/30 mm) and rotating shutters for speed determination. The LLLTV systems consist of S-VHS commercial video cameras, 2nd generation image intensifiers (Dedal 41) and various types of objectives according to the purpose and configuration of the planned observations. These direct light observing systems are usually accompanied at Ondřejov station by one spectral LLLTV camera and a battery of six photographic spectral cameras covering, however, only a part of the sky. Since August 1999, three radiometers are regularly operated at Ondřejov and Kunzak observatories (Spurný et al., 2001). Detailed radiometric lightcurves with very high time resolution (1200 s^{-1}) are available for

six of the presented meteors. The light curves cover only the brightest parts of the meteors (above -5 mag). As well as exact determination of the time of fireball passage, these records are useful for detailed study of short flares and determination of radiometric maximum brightness.

There are also other instrumental records of some of the presented meteors. A strong radar head echo and body echo was detected for meteor EN130801C. Moreover, at least the two brightest meteors from our list (EN130801A and EN010803) were detected by the infrasound array IS26 near Freyung in Germany (Edwards and Brown, private communication). These observations have not been analyzed yet and will be discussed in future papers.

Basic data on the 8 bright meteors simultaneously observed by different instruments are shown in Table I. This Table contains the date and time of each fireball, atmospheric trajectory data such as beginning, maximum light and terminal heights for both photographic and TV observations (denoted H_B or H_E (TV or Ph), $H_{\max}$), their differences (DH), distances of the beginnings from TV cameras (R_B (TV)), lengths of the observed luminous paths (L), initial speeds ($V_{\inf}$), maximum photographic ($MP_{\max}$) and radiometric ($MR_{\max}$) absolute brightnesses, photographic photometric masses (Mass) and slopes of the trajectories to the horizontal. Table I continues with data on geocentric radiant represented by right ascensions (RA), declinations (DE) and initial geocentric velocities (V_g) and sets of six orbital elements ($a, e, q, \omega, \Omega, i$), which represent heliocentric orbits of all presented meteors. All these radiant and orbital data are given in J2000.0 equinox. The last row is devoted to shower membership. Asterisks at some values of terminal TV heights mean that this is not real observed terminal height because meteor left the FOV of TV camera.

2. Beginning Heights and Lightcurves from TV and Photographic Cameras

All observed meteors exhibit great differences between photographic and TV beginning heights. The differences are represented by value DH in Table I and plotted in Figure 1. For all six meteors with beginnings recorded by both photographic and TV cameras, TV records started much higher than the photographic ones. This effect was already found for Leonid meteors by Spurný et al. (2000a). In the present case the differences range from 29 km to almost 50 km for the brightest meteor. This is caused mostly by different magnitude and spectral sensitivities of both observing systems.

Because sensitive image intensifier cameras are able to detect meteors much higher in comparison with the photographic cameras, they provide us with the opportunity to study earlier parts of the luminous meteor trajectory. The time resolution of the equipment used is 0.04 s. Unfortunately, rather

TABLE I
Basic atmospheric trajectory data, geocentric radiant and orbital elements (J2000.0) of 8 bright meteors recorded simultaneously by TV and photographic cameras (values in parentheses are uncertain)

Meteor	EN090897	EN120897	EN110800	EN120801	EN130801A	EN130801C	EN150801	EN010803
Date	9.8.1997	12.8.1997	11.8.2000	12.8.2001	13.8.2001	13.8.2001	15.8.2001	1.8.2003
Time (UT)	22:57:58	0:16:24	22:11:49	22:12:03	23:29:45	22:45:54	21:56:53	22:18:54
H_b (TV) (km)	–	–	149.0	145.1	160.7	137.4	139.3	142.9
H_b (Ph) (km)	104.3	107.0	103.0	107.2	111.4	(91.0)	110.5	109.5
DH (km)	–	–	46.0	37.9	49.3	46.4	28.8	33.4
H_E (TV) (km)	–	–	90.9*	108.3*	119.7*	78.7	85.5	98.2*
H_E (Ph) (km)	81.5	76.2	87.6	79.2	68.7	79.6	86.4	83.9
R_b (TV) (km)	–	–	184.5	179.9	268.2	161.8	154.7	159.8
L (km)	33.7	39.4	93.9	102.2	134.1	90.2	70.8	170.5
V_{inf} (km/s)	60.0	60.1	59.9	57.5	60.0	59.9	54.2	68.8
MP _{max}	–7.4	–7.8	(–6.0)	–7.9	–12.8	–6.9	–6.6	–8.1
MR _{max}	–	–	–5.2	–7.3	–11.8	–6.6	–6.5	–7.7
H_{max}	84.1	80.9	91.6	81.5	75.5	(79.0)	89.2	96.1
Mass (g)	16	10	(7)	16	600	3	2	24
Slope (deg)	42.5	51.4	37.8	40.3	43.0	40.6	49.5	19.9
RA (deg)	43.05	46.39	45.7	0.22	52.12	49.8	24.59	39.38
DE (deg)	57.96	57.39	58.7	21.16	59.50	59.5	67.11	35.51
V_g (km/s)	58.84	58.95	58.8	56.17	58.8	58.7	52.9	67.60
a (AU)	21	11.1	12	16	33	24	27	37
e	0.956	0.914	0.92	0.984	0.97	0.961	0.96	0.974
q (AU)	0.9580	0.9541	0.959	0.264	0.933	0.9481	1.0120	0.9576
ω (deg)	152.57	151.4	152.7	299.4	147.2	150.4	176.97	152.3
Ω (deg)	137.41124	139.38230	139.52175	140.23560	141.24775	141.21850	143.10769	129.20993
ι (deg)	111.98	113.58	113.0	119.4	111.5	111.3	95.0	146.72
Shower	Perseid	Perseid	Perseid	Sporadic	Perseid	Perseid	Sporadic	Sporadic

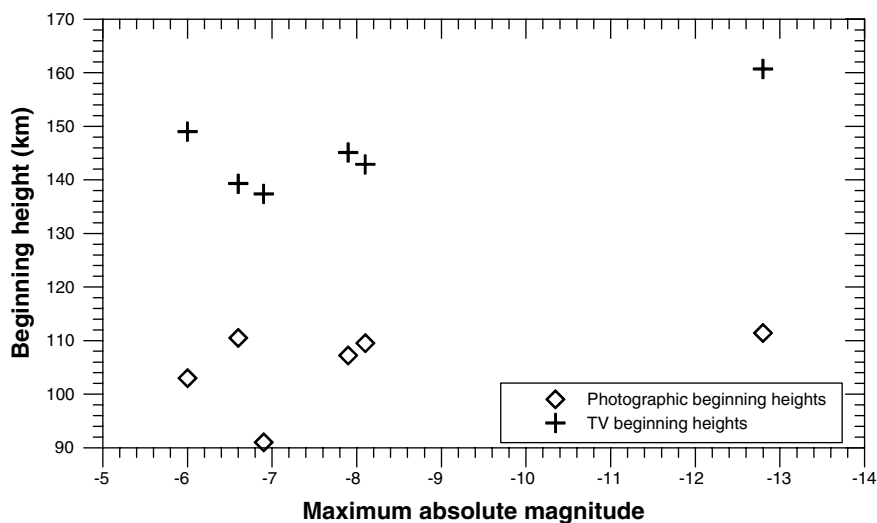


Figure 1. A comparison of beginning television and photographic heights and their dependence on photographic maximum absolute magnitudes.

small field-of-view of our intensified cameras usually resulted in only partial coverage of the bright meteors reported here.

The beginning parts of six meteors from our sample were recorded by the LLLTV cameras. Light curves of two of them are shown in Figure 2 together with the photographic light curves, which cover only the bright portion of the luminous trajectory.

The light curves of all meteors show similar behavior to that reported for the Leonid meteors with very high beginning heights (Spurný et al., 2000b). Above 130 km the meteor brightness fluctuates. Around 130 km the situation changes and the light curves become smoother. Also the meteor appearance usually changes around this height. Rather diffuse structures observed above 130 km gradually disappear and we can observe the typical meteor appearance usual in the case of the standard meteors.

We found a difference of about 2 magnitudes between the meteor brightness as measured on photographs and on TV records. The fireballs seem to be brighter on photographs. This is not a calibration error but a natural consequence of unequal spectral distribution of fireball light. Figure 3 shows the spectrum of the EN120897 Perseid fireball in the 370–900 nm range at the height of 83 km, just before the maximum brightness. The spectrum was reconstructed from overlapping higher spectral orders (2nd and 3rd) in the TV record. We had to use these data because the spectra of the fireballs, recorded in the 1st order, were saturated near the maximum brightness. The normalized spectral sensitivities of photographic, video, and radiometric systems are also shown in Figure 3.

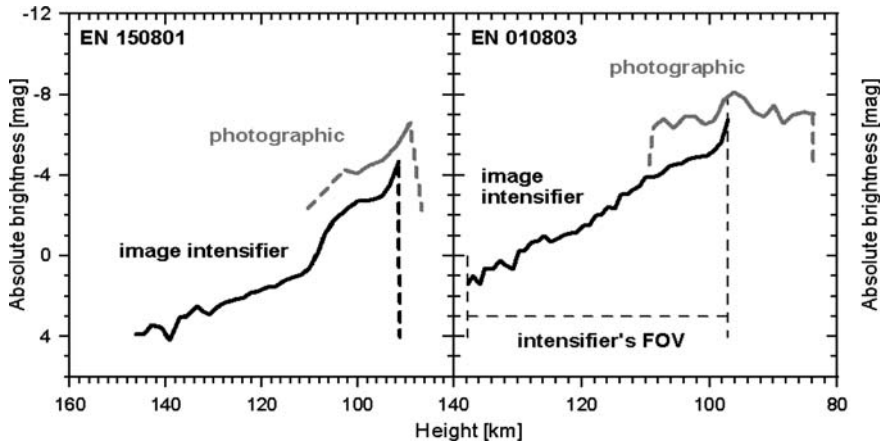


Figure 2. The light curves of the meteors EN 150801 and EN 010803. The black lines show image intensifier light curves, the grey ones light curves constructed from the photographic records. In the case of the EN 010803, meteor entered and again left field-of-view of the image intensifier camera. The dashed lines do not represent actually measured brightness but its approximation below the sensitivity limit of detector.

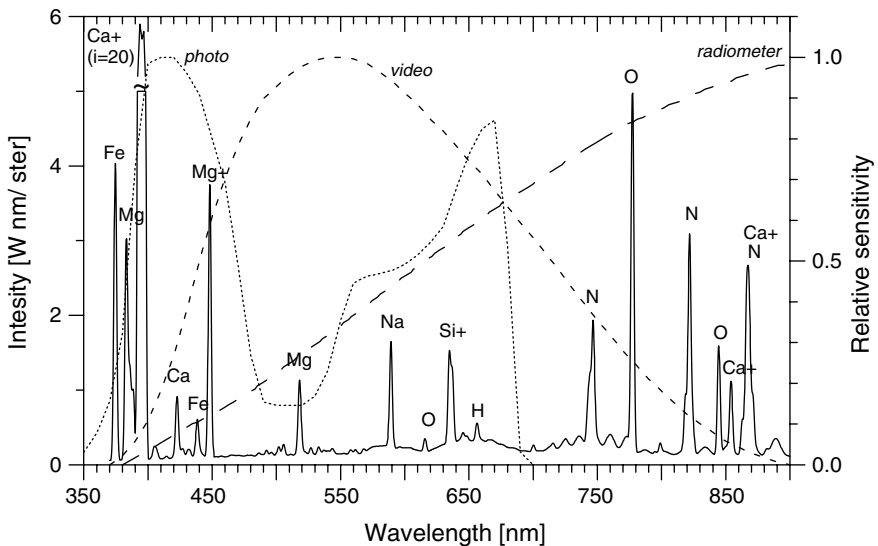


Figure 3. The spectrum of the EN 120897 fireball at the height of 83 km (just before maximum brightness) as reconstructed from the video observation in the 2nd and 3rd spectral orders. The main lines are identified. Note that the Ca^+ line intensity at 395 nm is out of scale. The normalized spectral sensitivities of the photographic, video, and radiometric systems are also given. The uncertainty of the intensities of the lines lying at the edge of the video sensitivity can reach 50%.

A majority of fireball radiation comes from a relatively small number of individual atomic lines. By far the brightest line is the ionized calcium doublet at 393 and 396 nm. This line is well inside the sensitivity range of the photographic camera but at the edge of the sensitivity of the TV system. The situation is similar with other bright lines in the blue region. The region where the TV system is most sensitive contains, on the other hand, only a few less bright lines. This is the reason why fireballs are fainter in the TV record. Note, however, that this conclusion applies to bright and fast fireballs only. The high temperature spectral component that the Ca^+ line belongs to is not present in slow or faint meteors (Borovička, 1994; Borovička et al., 1999).

According to the simple empirical formula derived in Spurný et al. (2001), we can also determine brightness from radiometric records. As shown in Table I, these values agree well within the errors of both methods and we have thus confirmed the validity of this formula for fast meteors. The formula is different for slow meteors with different spectral distribution of light.

The application of our standard photographic photometry (measurement of trail width) failed for the meteor EN110800. The trail seems to be diffuse. Indeed, the TV record indicates some diffuseness and even jet-like features in the meteor head during the bright part of the meteor. A similar effect was already described for Leonid meteors by Taylor et al. (2000). Therefore the maximum photographic magnitude and initial mass of this meteor in Table I are only estimates and are in parentheses. It is worthwhile to note that the TV beginning for this meteor was quite high for the meteor brightness (Figure 1).

3. Time Evolution of Fireball Spectra

The spectra of the meteors change along the trajectory. We were able to measure the spectral line intensities in that part of the TV records where the spectrum lay in the field of view and was not saturated. From these data we have drawn some conclusion which seem to be generally valid for high velocity fireballs.

The lines of the high temperature meteoric component (Ca^+ , Mg^+ , Si^+ , Fe^+ , H) are strongest at lower heights and especially in meteor flares. Atmospheric lines (O, N), on the other hand, show the smallest brightening toward the end of trajectory and in flares. This effect was noted earlier (e.g. Borovička and Betlem 1997).

At higher heights (> 110 km), the Na line is usually brighter than the Mg line, while at lower heights, both lines have comparable brightness. The Na is not exhausted before the end of the trajectory, as is the case in many faint Leonids (Borovička et al., 1999).

Of particular interest would be the spectra at extreme heights (> 130 km). Unfortunately, no spectra were taken at this part of the trajectory for the meteors studied here. We have obtained, nevertheless, some spectra of Leonid fireball beginnings with the same instrument (unpublished). The spectra show that the main contributor to the high altitude radiation is the oxygen line at 777 nm together with a faint continuum. The position of the continuum is consistent with the N_2 molecular bands which are strong in normal Leonid spectra (Borovicka et al., 1999). The unambiguous identification of the continuum was, nevertheless, not possible. Both O and N_2 are of atmospheric origin. Sometimes, the meteoric Na line also appears above 130 km, while the Mg line always starts lower.

4. The Spectra of Fireball Trains

It is usual for fast meteors to leave a luminous train in the sky. The visibility of the train ranges from less than a second for faint meteors to more than an hour for some very bright fireballs. The luminosity of short-duration trains of faint meteors is produced exclusively by the green forbidden line of atmospheric oxygen at 557 nm (e.g. Millman et al., 1971). On the other hand, three phases have been identified in the evolution of persistent trains of fireballs (Borovicka and Koten, 2003). The afterglow phase is produced by low excitation metallic lines, while the subsequent (much fainter) recombination phase contains also lines of higher excitation, in particular the Mg line at 518 nm. The final and longest chemiluminescence phase is characterized by molecular emissions.

We captured the spectra of the trains of the EN 130801C and EN 150801 meteors. The duration of both trains was only a few seconds. The chemiluminescence phase did not develop. The trains formed at the position of meteor maximum brightness, which was 80–83 km and 90–95 km, respectively. Only the 557 nm line extended to higher altitudes. The spectra of both trains are given in Figure 4. They clearly differ by the presence of the Mg line in the EN 130801C train. Also the temporal evolution, presented in Figure 5, was different. The EN 130801C train shows initial brightening of the Na and especially the Mg line.

We interpret these differences as being caused by the significance of the recombination process in producing the metallic line intensities in the EN 130801C train, in contrast to the EN 150801 train. The recombination rate is proportional to electron density but decreases with increasing temperature. It therefore reaches its maximum some time after fireball disappearance, when the temperature has decreased and electron density is still relatively high. This is the reason for the initial rise of line intensities. The difference between the behaviors of both trains is probably caused by their

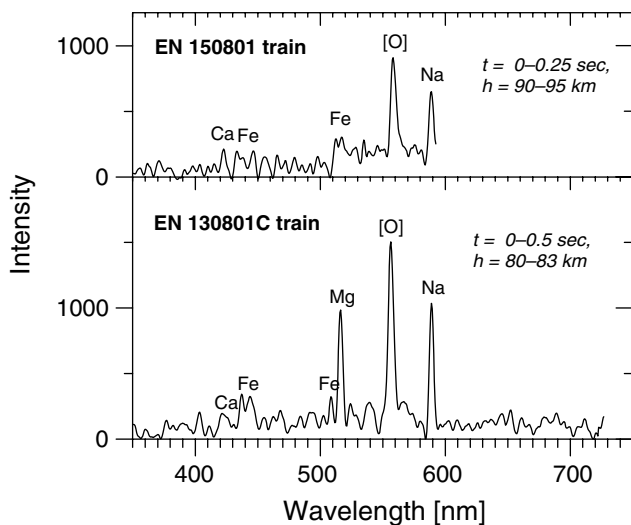


Figure 4. Video spectra of two fireball trains shortly after their formation. Presented spectra were summed over the height and time intervals indicated. Intensities are in arbitrary units not corrected for spectral sensitivity of the video camera (see Figure 3).

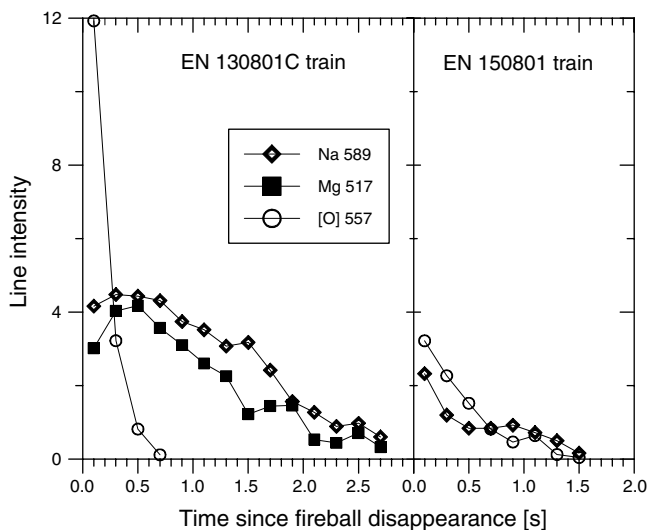


Figure 5. Temporal evolution of intensities of the main emissions in two fireball trains. To reduce the noise, measurements were done on averages of five video frames. Temporal resolution is therefore 0.2 s. The same height intervals as in Figure 4 apply. Intensities are in arbitrary units corrected for spectral sensitivity of the camera.

different altitudes and by different amounts of meteoric vapors deposited. The former meteor was a Perseid and the latter was sporadic, nevertheless, the initial mass, velocity and trajectory slope was similar in both cases. The spectra of the meteors do not show any significant difference in chemical composition of the meteoroids. The resulting difference in terminal height was therefore most likely caused by different structure and ablation properties of both meteoroids.

5. Conclusions

From analysis of 8 bright meteors detected by TV and photographic cameras we found the following results:

- (1) Photographic beginnings are practically constant for all presented meteors and TV beginnings are about 30–50 km higher.
- (2) Meteor brightness is up to 2 magnitudes higher in the photographic system than in the TV system. For high-velocity meteors studied in our sample, this difference is caused by the presence of strong Ca^+ lines in the blue part of the spectrum, where the image intensifier is only marginally sensitive.
- (3) Two captured spectra of short duration luminous trains differ in the presence of the Mg line at 518 nm. This line is the indicator of the importance of the recombination process in supporting train luminosity. The recombination also demonstrates itself by a small initial brightening of the Mg and Na lines in the train. The difference between the trains was probably caused by the different heights at which they were formed.
- (4) The lines of the high temperature meteoric component are strongest at lower heights and especially in meteor flares. Atmospheric lines, on the other hand, show the smallest brightening toward the end of trajectory and in flares.
- (5) At higher heights (> 110 km), the Na line is usually brighter than the Mg line, while at lower heights, both lines have comparable brightness. The dominant emissions above 130 km are the O line and N_2 bands, with some contribution from the Na line.

Acknowledgements

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OPTICAL TRAIL WIDTH MEASUREMENTS OF FAINT METEORS

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Abstract. We report results from two station, short-baseline (<100 m) high resolution measurements of faint meteors (limiting meteor magnitude $+9$) with the goal of measuring their optical trail widths. Meteors were observed using two 0.40 m Newtonian telescopes (field of view ~ 0.4 degrees) equipped with image intensifiers. Both telescopes were vertically oriented in a fixed mount and pointed to the same field of view. One system used a gated image intensified camera allowing the transverse velocity component to be measured. The widest trail captured, out of a total of 34 common events measured by both optical systems, had a full-width to half-maximum of 1.37 ± 0.71 m. The widest trail overall was captured by the gated system only, and was found to have a full-width of ~ 10 m. The brightness variation across this trail was found to be best represented by a Lorentzian. Most trails were smaller than our resolution limit and hence we could only place upper limits on their optical width. These were generally less than 1 m after correction for instrumental effects. Four meteors were found to have heights near 65 km and very low transverse velocities. These may be indicative of a largely unreported high density asteroidal component at these faint meteor magnitudes.

Keywords: Meteor, meteor heights, meteor velocities, optical, trail width

1. Introduction

Previous observations of meteor trail widths (Hawkins and Whipple, 1958; Cook et al., 1962) have produced results which suggest that the optical trail width for relatively bright (mainly $+5$ and brighter) meteors are larger than would be expected if the meteoroid were ablating as a single body. Measurements of meteor trail width for fainter meteors may thus provide direct evidence for the dustball theory (Hawkes and Jones, 1975) and could also add insight into the fragmentation and ablation process for small, sub-microgram meteoroids. Measurements of initial trail radii are crucial to the correction of radar observations as meteors whose initial radii are comparable to the radar wavelength being employed will be heavily attenuated (Ceplecha et al., 1998). The trail radii are also a key initial input parameter in

collisional and plasma models of meteors and meteor trail evolution (Dyrud et al., 2002).

2. Equipment

These data were collected over a total of six nights spread out over two observing runs in September 2003 and in May 2004, at the Elginfield Observatory (43°15'51 N, 80°46'20 W). Two identical f/4.5, 0.40 m aperture Newtonian telescopes were used, each having an effective field of view of $\sim 0.48 \times 0.34$ degrees. The two telescopes were vertically oriented in a fixed mount, and pointed at the zenith. The separation between the two telescopes was 27.5 and 105.2 m for the September, 2003 and May, 2004 observing runs, respectively. One of the telescopes was coupled with a gated digital image intensified CCD camera (QImaging Extended Blue Intensified Retiga). The pixel dimensions of the gated camera were 676×518 , with a resolution of 2.2 arc s/pixel. The main advantage of the gated camera is the ability to gate the image intensifier multiple times in a single CCD exposure. This records a meteor as a series of "dots" rather than a continuous trail, and allows for direct measurement of the velocity of the meteor as well as allowing a search for meteor wake to be made. For this experiment, the intensifier was gated at a frequency of 374.8 ± 0.4 Hz with a 1:4 on:off cycle yielding an effective exposure time of 0.5 ms per gated image. The Intensified Retiga had a limiting stellar magnitude of +12. Our other telescope was coupled to an NTSC video rate image intensified CCD sensor (ITT NightCam model 380i). The pixel dimensions of the video system were 720×480 pixels, and the resolution was $\sim 2.4 \times 2.6$ arc s/pixel. The CCD was used in an interlaced mode with 60 video fields (or 30 complete video frames) per second. The limiting stellar magnitude of the video camera system was +13.

3. Data Reduction

Meteors were identified from NTSC digital video tape data using Meteor-Scan 280c (Gural et al., 2002). A total of 87 meteors were detected, and of these, 56 were captured by both camera systems. The low number of dual detections is due to the difference in sensitivity, as well as a slight offset of the two fields of view.

Width measurements were made using two different methods. The first involved a direct measurement of the full-width at half-maximum (FWHM) of the intensity profile across the meteor trail. This method was useful for examining the core brightness of the intensity profile. For those meteors

which were detected by both camera systems, the parallax of the meteor was measured and heights obtained. Typical errors in individual height measurements were $\sim 1\text{--}2$ km. The results are summarized in Table I. For comparison with the video data, the FWHM of a star of similar brightness is included. We assume the point spread function (PSF) of the meteor trails will typically be smaller than stars of comparable brightness due to the much shorter exposure times for meteor trails. Thus the stellar widths actually represent an upper limit that can be attributed to the seeing ($1\text{--}2$ pixels) and instrumental blooming. Any remaining spread we attribute to physical width of the optical trail. The remaining spread for each meteor was calculated by subtracting the FWHM of a star of similar brightness from the FWHM of the meteor trail. The measured heights for each meteor were used to convert this correction from units of pixels to meters, which can be seen in the last column of Table I.

The second method involved summing up the total intensity along the entire major axis of the meteor trail, and moving this pixel wide “box” across the trail to produce a width profile. This second method yields greater widths if there are short duration light curve irregularities with measurable transverse deviation from the trail, as suggested in some of the meteors analyzed by Fisher et al. (2000). In this way we may examine the trail for evidence of a bright core with fragments ablating on either side. Very few meteor trails showed significant width relative to stellar profiles. Of particular note, however, is a meteor recorded at 08:00:47 UT on October 1, 2003 by the gated camera which shows an extended total width to the background of more than 16 m, assuming a height of 90 km. This trail, which was too faint to directly measure the height or the FWHM using the first method, has sufficient width that we can characterize the form of the light production across the trail. This was found to be best fit with a Lorentzian of the form $8.56/(1 + (x/6.62)^2)$ in units of meters. All other trails had too few points across their intensity profile to allow any meaningful fits to be attempted.

Figure 1 shows the height distribution of the 34 (of 56) meteors from our sample for which we were able to make height measurements. The mean height is 83 km, as there were no very high meteors (above 115 km) detected. However, a large population of high altitude meteors as proposed by Olsson-Steel and Elford (1987) should have been detected providing their trail widths were not exceptionally large or optical brightness very low. Note that there are quite a few events at heights $\sim 65\text{--}75$ km. To our knowledge these are the lowest heights ever measured for meteors in this magnitude range ($+8$ to $+9$).

Meteor velocities were measured for all meteors captured as a relatively clear series of dots on the gated camera for which height measurements were available (20 meteors in total). It should be noted that this measurement

TABLE I

Summary of Trail Width Measurements: observations made on Sept. 30 and Oct. 1, 2003, and May 13, 17, 19, and 27, 2004

Time (EDT)	Video meteor FWHM (pixels)	Error (pixels)	Star FWHM (pixels)	Gated meteor FWHM (pixels)	Error (pixels)	Height (km)	Height δ (km)	Corrected video meteor FWHM (m)
<i>Sep-03</i>								
1:47:04	3.16	0.77	2.68	2.80	0.96	65.2	1.7	0.50
3:31:30	na	na	na	3.92	1.41	88.0	3.1	na
3:37:07	na	na	na	5.87	0.77	104.4	6.6	na
3:45:05	3.29	0.73	2.68	2.33	0.58	111.7	11.1	0.88
3:50:06	3.73	0.78	2.68	2.88	0.43	83.5	2.6	0.88
4:13:09	3.29	0.97	2.68	2.24	0.00	110.9	3.9	0.65
4:17:53	4.23	1.13	2.68	2.98	0.94	70.4	1.2	0.96
4:41:41	2.86	0.96	2.68	2.56	0.32	93.0	5.0	0.12
5:11:29	3.87	1.06	2.68	3.69	1.09	80.9	2.7	0.75
5:13:29	na	na	na	3.36	0.59	64.5	1.5	na
5:18:20	3.56	0.68	2.68	2.35	0.48	65.6	1.0	0.35
5:24:23	3.32	0.53	2.68	3.67	0.49	107.9	8.2	0.42
1:50:16	2.95	0.91	2.90	na	na	67.2	1.2	-0.54
2:41:26	2.75	0.52	2.89	2.70	0.65	80.7	3.0	-0.92
3:21:42	3.72	1.28	2.90	2.81	0.91	77.4	3.1	-0.03
3:36:45	na	na	na	2.62	0.29	67.0	1.3	na
3:41:43	5.55	0.64	2.89	6.49	1.33	105.7	3.9	1.37
4:00:43	na	na	na	na	na	66.3	1.9	na
4:05:30	2.46	0.45	2.89	na	na	82.7	3.0	-1.03
4:26:19	4.84	0.80	2.90	5.18	0.78	81.4	2.8	0.58
<i>May-04</i>								
4:22:24	3.03	0.65	3.23	2.88	0.47	83.0	0.9	-0.78
2:15:42	4.06	0.54	3.23	na	na	74.6	0.4	0.20
0:47:30	3.53	0.76	3.24	2.66	0.48	97.6	2.8	0.24
1:01:34	3.55	0.85	3.24	3.02	0.80	81.5	0.5	-0.20
1:19:57	na	na	na	2.89	0.82	68.7	1.7	na
1:59:56	3.63	0.98	3.24	na	na	79.3	0.5	0.04
23:05:29	4.14	0.76	3.24	3.15	1.00	95.8	2.4	0.60
23:07:18	3.13	0.39	3.23	na	na	86.6	0.6	-0.71
23:19:37	3.09	0.65	3.23	na	na	87.5	0.7	-0.67
1:10:42	na	na	na	2.90	0.64	78.2	0.4	na

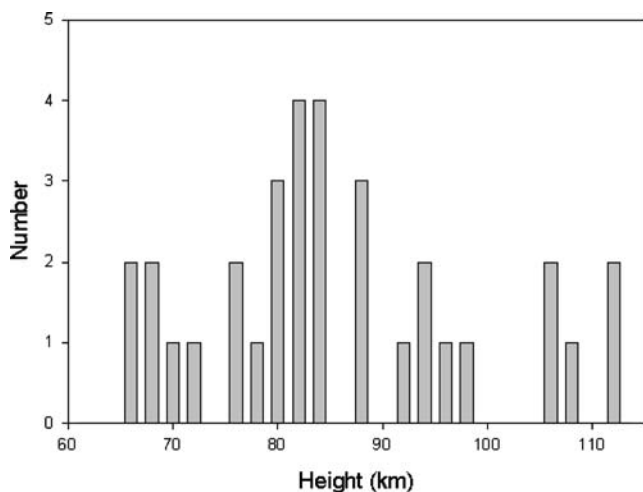


Figure 1. Height distribution of meteors in the sample.

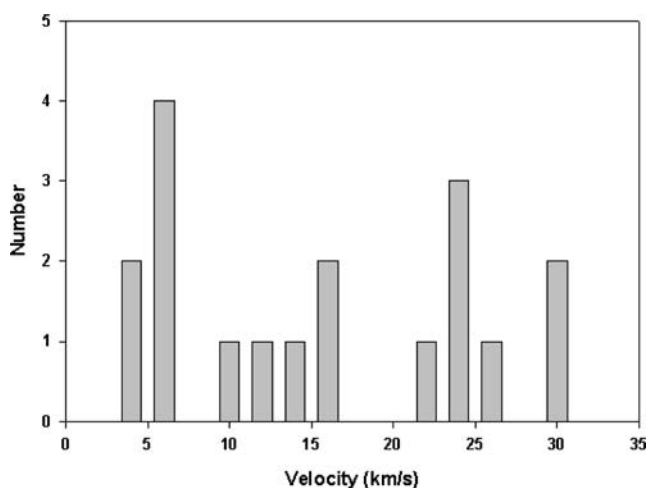


Figure 2. Velocity distribution.

represents only the transverse (sky plane) component of the true velocity; the actual velocities will be larger. Figure 2 is a plot of the velocity distribution with an average error per measured meteor velocity of 0.6 km/s. The lowest velocities (~ 5 km/s) generally correspond to the low height population (below 70 km).

Meteor magnitudes were measured only for those meteors which were clearly gated (showing little or no wake between dots) so that standard differential stellar photometry techniques could be used (total number = 11). The absolute magnitude range was found to be $\sim +6.5$ to $+10$.

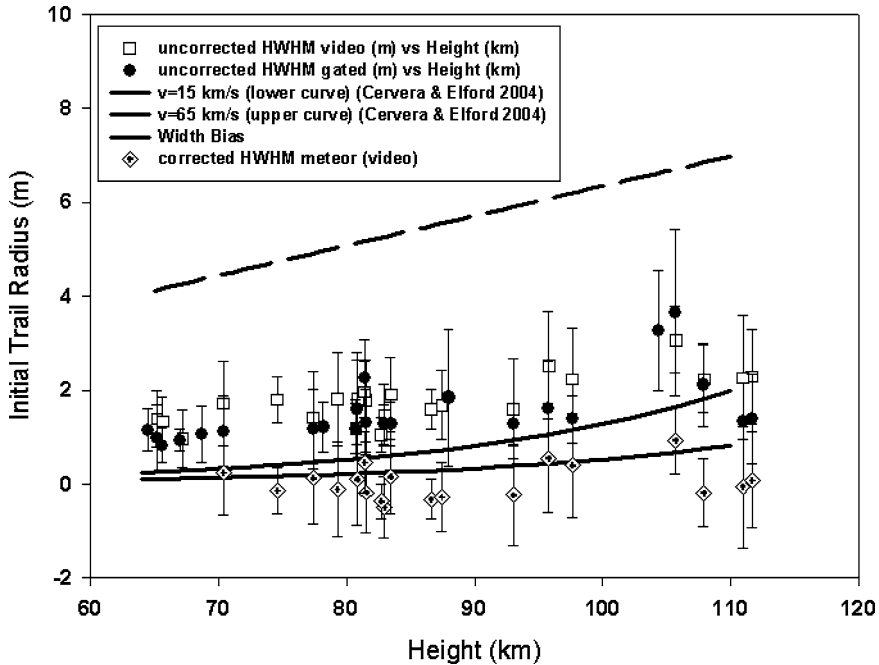


Figure 3. Height versus Initial Trail Radius. This figure displays our results along with predictions of trail radii versus height from Cervera and Elford (2004). Also included is our calculated width bias, which is an estimate of the widest trail radius we expect to be able to detect with our equipment. The uncorrected HWHM represent the trail radii without correcting for atmospheric and instrumental broadening, while the corrected HWHM have been corrected for such effects.

4. Discussion and Results

Figure 3 is a plot summarizing all the width measurements made for both the video and the gated images (using only the first width measurement technique). Note that the width measurements have been converted from full-width to half-width (trail radii) in order to compare to published results. The uncorrected trail radii represent an upper limit to the true radii as no corrections have been applied for widening caused by seeing and instrumental blooming. For comparison, an estimate of the widest meteor trail we expect to detect with our instrumental setup was determined by using the brightest meteor detected during our campaign, and summing its total intensity along the major axis of the trail in a rectangle three pixels wide. This total intensity was then spread out over successively larger and larger rectangular areas, until the average intensity per pixel dropped to within one standard deviation of the mean background (i.e., until it was just barely detectable). We defined

this to be our width bias, which is shown in Figure 3 represented by the dashed line.

Also included are points representing the corrected trail radii values for which the radius of a star of similar peak intensity has been subtracted to account for the seeing and instrumental blooming. For comparison, there are two curves plotted among the data in this figure representing predicted initial trail radii at various heights with velocities of 15 and 65 km/s using the relation from Cervera and Elford (2004):

$$\log_{10} r_0 = 0.0194h - 1.96 + 0.6 \log_{10}(v/40) \quad (1)$$

where r_0 is the initial radius (root mean square width) of the meteor trail, h is the height in km, and v is the velocity in km/s.

There were four events (5% of the total sample) which were found to produce light at very low heights (~65 km). Single body ablation modeling shows that meteoroids of this mass (less than a microgram) need to have very high heats of ablation to penetrate to this altitude. Indeed, almost the only means to model such deep penetrations is to assume material with properties comparable to solid iron. We adapted the ablation model of Rogers et al. (2004) submitted, to investigate what heights would be predicted for low velocity, high density meteoroid ablation. If iron (density 7800 kg/m³) spherical particles are assumed, maximum luminosity is observed at a height of 68, 72, and 76 km for 10⁻⁴, 10⁻⁵, and 10⁻⁶ kg meteoroids.

These low events were also found to have very low transverse velocities ~5 km/s, and showed no evidence for significant width or measurable wake. Potentially, we are detecting a previously unseen large population of small, low velocity (and hence faint) meteors of largely iron composition. We do not know of any previous surveys (radar or optical) which would be expected to detect such a faint, low and slow meteoroid population.

5. Conclusions

In total, 87 meteor trails were examined, most of which showed little to no statistically significant width (i.e., width beyond that of a star of similar brightness). The widest trail found by directly measuring its corrected FWHM (method 1) was found to be 1.37 m ± 0.71. Using a slightly different method which involved summing up the total intensity along the meteor trail, we were able to look at meteors that had been too faint to be measured using method 1. As a result, we were able to determine that the widest trail captured (08:00:47 UT on October 1, 2003) had a corrected full width of ~10 m.

No meteors were detected at very high altitudes. The greater range to high meteors result in reduction of apparent brightness according to the inverse

square law, and more high meteors will be lost in the unresolved background glow. It is possible that there is a second bias if the trail widths increase at great heights due to a larger mean free path. The four low events detected at ~65 km could represent a population of asteroidal material not yet previously detected. These meteors at low heights also had very low transverse velocities, characteristic of a low height population.

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HIGH SPATIAL AND TEMPORAL RESOLUTION OPTICAL SEARCH FOR EVIDENCE OF METEOROID FRAGMENTATION

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Abstract. A digital image intensified CCD camera with an electronically gated image intensifier was used to produce very short duration images of meteors. The observational system employed a 0.40 m F/4.5 Newtonian telescope to obtain high spatial resolution. A second intensified CCD camera was used to yield height information using parallax. At a typical meteor height one pixel (for the vertically oriented system) corresponded to about 1.1 m. A sampling of 59 mainly sporadic meteors was analyzed. There is clear variability from meteor to meteor, with many meteors (nearly 50%) showing only a small amount of wake, while some meteors (approximately 20%) have the off segments completely filled in.

Keywords: Ablation, fragmentation, high resolution, meteor, structure, wake

1. Introduction

The classical papers on wake (the degree to which the instantaneous light production region of a meteor is not a point source) have considered both photochemical (Halliday, 1958) and fragmentation and lag (McCrosky, 1958) mechanisms. The quantitative dustball model (Hawkes and Jones, 1975) predicts that cometary meteoroids should cluster into constituent grains during or prior to atmospheric ablation. Unless the size distribution of these grains is uniform, differential aerodynamic drag would be expected to produce wake (Fisher et al., 2000). Observational evidence of wake in faint meteors has proven to be elusive however, with most studies indicating only a small percentage of faint meteors with detectable wake (Robertson and Hawkes,

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1992; Shadbolt and Hawkes, 1995; Fisher et al., 2000). In this study we used significantly improved spatial resolution accompanied with very short duration exposures to search for wake in faint meteors.

2. Equipment

A digital image intensified CCD camera (Intensified Retiga) with an electronically gated image intensifier was coupled to a 0.40 m F/4.5 Newtonian telescope to obtain high spatial and temporal resolution. The intensifier was gated in a mode with the gate on for exactly 1/5 of the exposure and off for 4/5 of the exposure time, and the repetition rate was 375 Hz. Therefore, the effective length of each exposure was 0.53 ms. The P43 phosphor used in the image intensifier has persistence of approximately 10% after 1.2 ms (however, because of the gating mode used in the intensifier the persistence is not really an issue in any case). The image covered 24.8×19.0 arc minutes (and in the mode used 676×518 pixels) so that at a typical meteor altitude one pixel (for the vertically oriented system) would correspond to about 1.1 m. A nongated video rate intensified CCD camera was mounted at a second location to yield height information for coincident events using parallax (Kaiser et al., 2005). Corrected meteor magnitudes were generally in the range from +8 to +10 magnitude (Kaiser et al., 2005) while apparent stellar limiting magnitude was +13 to +14 over the observing period. Samples of observed meteors are shown in Figure 1.

3. Analysis and Results

A sampling of 59 mainly sporadic meteors from September and October 2003 and May 2004 were analyzed (see Tables I and II). Sky conditions were

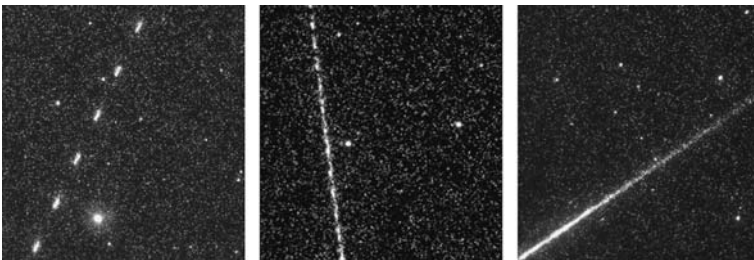


Figure 1. Classification system used for the data. A meteors have clear on and off segments as shown in the left image. W-meteors have the off segments totally filled in with wake as pictured on the right. P-meteors, shown in the middle, have variable degrees of fill in the images.

excellent on the nights used for these observations. The companion paper by Kaiser et al. (2005) provides full width half maximum (FWHM) values for stars observed with the system, which typically are 2 to 3 pixels. Since the effective exposure of the meteor is so short (0.53 ms), a time short compared with most of the atmospheric induced scintillation, we would expect that image blooming due to the seeing for meteors will be even less.

As a first stage of analysis we classified each meteor into the following categories: A, all segments have clear on and off features; P, portions of the trail have the segments filled in while some indication of the gating is still visible; and W, full wake with all off segments filled in on the meteor images. In the overall sample, 30 meteors were of type A, 19 of type P and 10 of type W.

For each A-type meteor we obtained a luminous intensity plot using the full width of the meteor trail. Nearby regions were used to calculate a mean local background intensity and standard deviation. We defined regions with at least two successive values two standard deviations above the mean local background as on. We calculated a duty cycle fraction (f) for each light curve segment, defined as the fraction of each cycle which was on. The results are shown in Figure 2, with the length of each line representing $\pm 1\sigma$ values. A point source meteor would produce a value of 0.2. It is obvious that almost none of even the A meteors are consistent with a point-source hypothesis.

In order to obtain a measure of the minimum possible wake we used the following relationship (1 pixel corresponds to 1.1 m resolution at a height of 100 km):

$$w_{\min} = \frac{1.1\tau_p h}{100} (f - \sigma_f - 0.2) \quad (1)$$

Here $w_{\min}$ is the minimum wake component perpendicular to the line of sight, τ_p is the number of pixels in one cycle, h is the height (in km) of the meteor, f is the mean fraction of the cycle which is luminous averaged over all segments of the meteor, and σ_f is the standard deviation in f . We show in the last columns of the tables the minimum wake values for the A-class meteors.

It is not possible to give photometric masses or peak luminosity absolute magnitudes for these meteors since they are observed for only a small portion of the total light curve. The companion study by Kaiser et al. (2005) suggests that the absolute meteor magnitudes fall in the range from about +8 to +10. We do provide in Tables I and II the peak brightness of each meteor (averaged transverse to the trail) on an arbitrary scale with higher numbers corresponding to brighter meteors. This provides the reader with some indication of the relative intensity.

TABLE I
Data for 2003 telescopic gated observations

Date	UT	Type	f	ω	τ_p	h (km)	I	$w_{\min}(\text{m})$
9/30/03	5:36:02	A	0.43 ± 0.08	5.0 ± 0.6	21.90	90.0	140	3.3
9/30/03	5:37:03	A	0.37 ± 0.09	17.9 ± 3.1	78.00	90.0	62	6.2
9/30/03	5:47:04	A	0.34 ± 0.04	5.9 ± 0.4	25.67	90.0	118	2.5
9/30/03	5:55:07	W						
9/30/03	6:05:22	P						
9/30/03	6:35:24	A	0.31 ± 0.05	29.6 ± 2.1	129.00	75.0 ± 3.3	98	6.4
9/30/03	6:43:22	P						
9/30/03	6:53:30	P						
9/30/03	7:31:30	P				88.0 ± 3.1		
9/30/03	7:37:07	W				104.4 ± 6.6		
9/30/03	7:45:05	A	0.32 ± 0.05	16.9 ± 1.3	73.60	111.7 ± 11.1	97	6.3
9/30/03	7:50:06	A	0.34 ± 0.07	8.8 ± 1.0	38.56	83.5 ± 2.6	122	2.5
9/30/03	7:50:37	W						
9/30/03	8:08:50	P						
9/30/03	8:13:09	P				110.9 ± 3.9		
9/30/03	8:17:53	A	0.29 ± 0.02	19.9 ± 1.1	87.00	70.4 ± 1.2	142	4.7
9/30/03	8:41:40	A	0.35 ± 0.05	9.4 ± 0.8	40.82	93.0 ± 5.0	93	4.2
9/30/03	8:46:54	A	0.29 ± 0.06	28.7 ± 3.7	125.00	90.0	80	3.7
9/30/03	8:59:24	A	0.25 ± 0.03	3.4 ± 0.3	14.62	90.0	74	0.3
9/30/03	9:04:42	W						
9/30/03	9:11:29	A	0.38 ± 0.05	8.6 ± 0.8	37.54	80.9 ± 2.7	150	4.3
9/30/03	9:13:29	A	0.33 ± 0.04	29.0 ± 1.4	126.50	90.0	119	11.3
9/30/03	9:18:20	A	0.34 ± 0.10	9.1 ± 1.9	39.67	90.0	97	1.6
9/30/03	9:23:53	A	0.29 ± 0.03	6.7 ± 0.2	29.08	90.0	105	1.7
9/30/03	9:24:23	A	0.48 ± 0.11	12.8 ± 1.8	56.00	107.9 ± 8.2	160	11.3
9/30/03	10:07:39	A	0.29 ± 0.06	30.5 ± 3.5	133.00	90.0	112	4.0
10/1/03	5:50:16	P						
10/1/03	5:57:00	A	0.24 ± 0.05	6.6 ± 0.8	28.95	90.0	135	-0.3
10/1/03	6:40:25	A	0.51 ± 0.05	10.1 ± 0.7	44.22	80.7 ± 3.0	141	10.2
10/1/03	7:06:31	P						
10/1/03	7:06:56	A	0.43 ± 0.10	10.2 ± 1.0	44.64	90.0	116	5.7
10/1/03	7:21:43	A	0.54 ± 0.02	17.9 ± 0.5	78.20	77.4 ± 3.1	138	21.3
10/1/03	7:31:08	A	0.20 ± 0.03	36.0 ± 3.1	157.00	90.0	85	-4.7
10/1/03	7:36:45	P						
10/1/03	7:41:43	P				105.7 ± 3.9		
10/1/03	7:42:59	A	0.27 ± 0.06	19.9 ± 3.0	86.80	90.0	167	0.9
10/1/03	8:00:43	A	0.56 ± 0.26	34.2 ± 13.8	149.00	90.0	100	14.8
10/1/03	8:05:30	A	0.53 ± 0.09	20.6 ± 1.5	90.00	82.7 ± 3.0	116	19.6
10/1/03	8:26:19	A	0.35 ± 0.03	16.0 ± 0.6	69.90	81.4 ± 2.8	178	7.5
10/1/03	8:44:20	W						
10/1/03	8:51:11	P						
10/1/03	9:00:28	W						

The date and universal time, the trail classification (A, clear breaks in each cycle; P, partially filled in breaks; and W, breaks completely filled in), followed by the fraction (f) of each cycle which is luminous above background and the standard error in that fraction, the angular velocity (ω) in degrees per second and its uncertainty. This is followed by the length of one cycle of the trail in pixels (τ_p), the height in km (if no parallax measurement was possible a standard height of 90 km was used in the analysis) and the standard error on the height measurement. The smoothed maximum intensity (I) of the meteor (arbitrary units) is given followed by the computed minimum wake perpendicular component $w_{\min}$ in the final column, expressed in meter.

TABLE II
Data for 2004 telescopic gated observations. Columns have same meaning as in Table I

Date	UT	Type	f	ω	τ_p	h (km)	I	$w_{\min}$ (m)
5/13/04	8:22:24	W				83.0 ± 0.9		
5/17/04	4:11:05	A	0.30 ± 0.04	6.8 ± 0.7	29.76	90.0	111	1.8
5/17/04	4:24:29	P						
5/17/04	5:53:13	A	0.30 ± 0.04	4.9 ± 0.3	21.33	90.0	78	1.3
5/17/04	6:15:42	A	0.67 ± 0.08	3.3 ± 0.2	14.35	90.0	150	5.5
5/20/04	4:47:34	P	0.34 ± 0.07	20.2 ± 4.3	88.00	97.6 ± 2.8	132	6.6
5/20/04	5:01:39	P				81.5 ± 0.5		
5/20/04	5:45:33	P						
5/20/04	5:45:33	W						
5/20/04	6:46:08	P				92.4 ± 2.2		
5/20/04	8:23:57	A	0.54 ± 0.08	4.3 ± 0.3	18.65	90.0	217	4.8
5/26/04	3:05:29	W				95.8 ± 2.4		
5/26/04	3:07:18	P	0.66 ± 0.09	4.3 ± 0.4	18.55	86.6 ± 0.5	133	6.5
5/26/04	3:19:37	A	0.31 ± 0.04	8.4 ± 0.8	36.47	87.5 ± 0.6	153	2.5
5/26/04	3:38:05	W				83.4 ± 3.3		
5/27/04	5:10:42	P				78.1 ± 0.4		
5/27/04	7:35:40	P	0.62 ± 0.11	4.3 ± 0.5	18.55	90.0	67	5.7

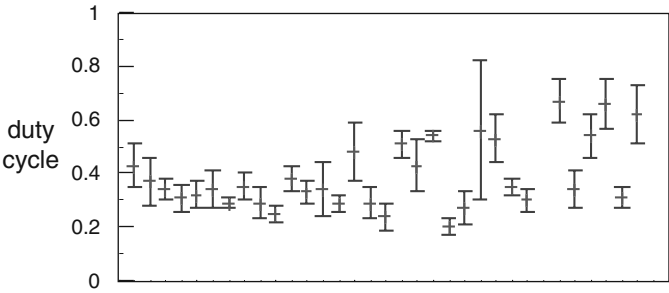


Figure 2. For A-type meteors the mean (averaged over all segments of the meteor light curve) fraction of the trail which has luminosity is plotted (the length of the line shows $\pm 1\sigma$). With our instrument a meteor with no wake would have 0.2 for the theoretical duty cycle with our equipment.

The velocity of the meteors cannot be determined, since the angle of the trail to the line of sight is not known. We plot in Tables I and II the angular velocity, ω which should be statistically related to the velocity. As shown in Figure 3, the amount of wake seems to increase with angular velocity of the meteor. This may suggest that cometary origin meteoroids, which would be expected to impact with higher geocentric velocities than meteoroids of asteroidal origin, produce larger amounts of wake.

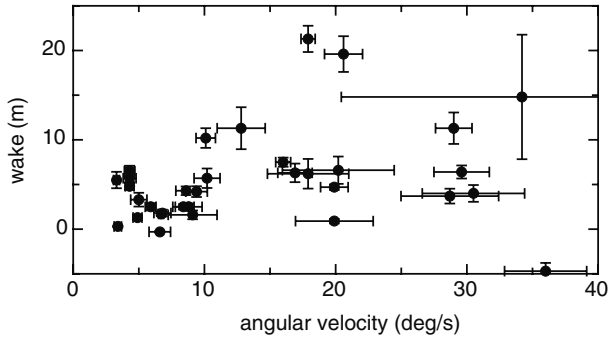


Figure 3. Plot of minimum apparent wake (in meters) versus the angular velocity (in degrees per second) for the A type meteors in this study.

4. Discussion

A powerful new tool for meteor science has been developed which permits simultaneous high spatial and temporal resolution optical studies of faint meteors. If the meteors observed here are typical, it has been shown that more than 50% of meteors in this magnitude range have spatial wakes of about 16 m or more (all of the W- and P- classified meteors, and a few from the A set), and almost all meteors have a small amount of wake which can be measured by this technique.

The most obvious question to ask is whether the wake measured here for A-type meteors is due to differential lag of dustball grains, or atomic excitation and decay over a distributed region. Monte Carlo techniques were used to model the flow field around a meteoroid by (Boyd, 2000). They found a region of elevated temperature and ablated vapor density extends much further along the longitudinal direction than transverse to the meteor trail (about 1–2 m transverse and 10–30 m longitudinal). Those results would be consistent with the wake values measured here, and with the finding of little evidence for optical trail width using the same equipment (Kaiser et al., 2005). However, it must be stressed that the masses of the meteors in the numerical simulations were more than a million times larger than the meteors studied here (the meteors in this study have masses of the order of 10^{-8} kg, although it must be stressed that with so little of the luminous path being captured photometric masses cannot be derived). Using an air beam model (Popova et al., 2000) came to somewhat similar conclusions to those of Boyd. They find that a dense vapor cloud around the meteoroid partially screens the meteoroid surface from direct impacts by air molecules. In their results while the temperature of the vapor has dropped by a factor of 2 in only a distance of 1 m, the temperature is still elevated to about 5500 K at a distance 5 m behind the meteor head. Clearly, additional work on meteor ablation theory is necessary before the nature of the wake observed in this study can be

definitively attributed to vapor interactions or to differential grain deceleration. We feel that at least the P- and W-type meteors probably require differential aerodynamic lag, and therefore this research supports the view that at least half of very faint meteors have a dustball structure.

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TV OBSERVATION OF THE DAYTIME METEOR SHOWER; THE ARIETIDS

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Abstract. We have carried out multi-station TV observations since 1994 in order to determine the orbit of the Arietid daytime meteor stream. In 1999, one possible Arietid meteor was recorded by our simultaneous observations and its orbit was determined. In 2003, two Arietid meteors were observed from two stations of our observing site, those orbits were determined precisely, the orbital elements were in good agreement with each other. This is the first time that determination of the precise orbit of the Arietids has been made from optical observations. The orbit of these Arietid meteors, and comparison with the orbit obtained from radar observations are discussed.

Keywords: Interplanetary medium, meteors, meteor shower, solar system

1. Introduction

The Arietids, active in early-mid June, is the strongest daytime meteor shower of the year. This shower was discovered by radar observations at Jodrell Bank in 1947. It is a very interesting meteor shower because of various discussions on the relation with other showers and their parent bodies (McKinley, 1961; McIntosh, 1990; Babadzhanov and Obruchov, 1992; Ohtsuka et al., 2003). It was pointed out from the orbit obtained from the earlier radar observations that the Arietid shower is from the same origin of the δ -Aquarids, observed between the end of July and the beginning of August, because of the similarity of the orbits (Almond, 1951). A candidate for the parent body is Comet P/Machholz.

Since the radiant point of the Arietids is close to the direction of the sun, all of the orbits of the Arietids presented by previous works depended only on radar observations. However, the Arietids can also be observed by optical techniques although the observation time window is limited to less than one hour before sunrise. The observation window becomes larger for TV observations compared with photographic observations because of the shorter

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integration time for TV observations. The zeta Perseids can also be observed by TV techniques (Ueda et al., 2001).

The limiting magnitude of TV observations is around +9 magnitude, which is less sensitive than the radar observations. However, the precision in the orbit determination for each meteor is better for the TV observations. The precision of the radar observations is 2° and 1% for radiant direction and meteor speed, respectively (McKinley, 1961). Typical two station TV meteor systems result in errors of order of 0.4° in radiant, 2 km s^{-1} in velocities (Hawkes, 1993). Physical characteristics of the Arietids can be obtained from the light curve and photometric data from TV observations.

In order to determine the precise trajectories and orbits of the Arietids, we planned multi-station TV observations. In addition, the simultaneous radar (MU radar) observation was planned in order to compare the data (Abe et al., 2004).

2. Observations

Multi-station TV observations were carried out for three nights on 2003 June 6–8. However, meteor images were successfully obtained only on June 7. The observation site and equipment are listed in Table I. The TV observation systems were equipped with second-generation (Gen 2) image intensifiers and digital video cameras with the NTSC format (30 interlaced video frame per second). The primary systems used in the observation had semi-long focus (85 mm) lenses which were same as those used in our TV observations since 1991 (Ueda and Fujiwara, 1995). High-sensitivity monochromatic CCD cameras (WATEC Co., type WAT-100N) were also used.

The limitation on our systems is the small field of view ($\Phi 16^\circ$). This could be increased through shorter focus length lenses. However, the observation with shorter focus length lenses (e.g. 24 mm; $\Phi 48^\circ$) suffers strongly the influence from background light (twilight) and angular resolution will be poorer (and hence the more uncertainty in such parameters as meteor trajectories) (Hawkes, 1990). For the reasons mentioned above, we used semi-long focus lenses.

TABLE I
List of the observing site and equipment

Id	Observing site	Camera designation	FOV ¹	LM ²
A	Muro, Nara	I.I. 85 mm F 1.2 lens	$\Phi 16$	8–9
B	Shigaraki, Shiga	CCD 25 mm F0.8 lens	10×14	7
C	Ohmihatiman, Shiga	I.I. 85 mm F1.8 lens	$\Phi 16$	8–9

¹Field of view (Φ : diameter, horizontal $\times$ vertical) in degrees.

²Apparent stellar magnitude.

On 2003 June 7, we started TV observations around at 17:00 UT. There was no serious interruption of the cloud throughout the observation. All of the observations were terminated at around 19:00 UT due to the light of dawn (Table II). There was no trouble of the image intensifier in the twilight conditions. The cameras were pointed to common volumes in the atmosphere (at 95 km above sea level in the center) to obtain double-station meteors.

In order to detect meteors, we replayed the recorded videotape twice. Moreover, the existence of the meteor image was checked one more time for the time meteor event recorded at the other observation site for the simultaneous observation between cameras A and B. After video images of meteors observed simultaneously were digitized on a PC, the positions and brightness of the meteors were measured. Further details of the procedures used for video data have been given elsewhere (Ueda and Fujiwara, 1995). The meteor trajectories in the atmosphere and the heliocentric orbits were calculated by a standard method (Hasegawa, 1983).

3. Result and Discussion

Two Arietids meteors were recorded at site A and B simultaneously by the TV cameras. Table III shows radiants, velocities and orbital elements derived from simultaneous TV observations in 2003. The TV observation data in 1999 (UF990112) is also included in the table, which was calculated for this study by measuring and reducing the image. Some radar data from literature are also listed in the same table, for comparison. The radiants and velocities for the two meteors observed in 2003 agree very well. It is notable that a very

TABLE II
Observational condition

Local time	E(1)	E(2)	LM(1)	LM(2)	Remarks
02:00	—	25	6	8	Observation start
02:30	0.0	21	6	8	
02:55	4.6	18	6	8	Dawn start
03:06	6.5	16	5	7	M03005
03:15	8.9	15	4	7	M03006
04:00	18.0	8	2	2	Observation end
04:42					Sunrise

Local Time : UT + 9 h.

E(1): Radiant elevation (in degrees) (Radiant: $\alpha = 42^\circ$; $\delta = +24^\circ$).

E(2): Elevation of the sun (minus in degrees).

LM(1): Limiting stellar magnitude with naked eye.

LM(2): Limiting stellar magnitude of TV system.

TABLE III
Radiant¹ and orbit² of Arietids

Name	Year	N^3	α	δ	V/g	q	e	i	Ω	ω	Reference
M03005	2003	–	42.5 ± 0.20	24.3 ± 0.11	41.5	0.07	0.97	30.74	76.548	27.11	
M03006	2003	–	42.0 ± 0.65	24.9 ± 0.29	42.6	0.07	0.98	35.74	76.554	27.12	
UF99012	1999	–	45.1 ± 0.19	25.6 ± 0.15	38.8	0.08	0.96	29.41	80.411	26.82	
L1	1950	–	44	22	38	0.10	0.94	18.0	77.7	29	Lovell (1954)
L2	1951	–	43	24	39	0.09	0.94	21.0	77.5	29	Lovell (1954)
DG60	1954	6	50	26	41	0.04	0.97	46.0	89.7	19	Davies and Gill (1960)
KL	1960	380	43	23	39	0.10	0.94	19.0	77.7	30.0	Kashcheev and Lebedinets (1967)
61.6.1	1961	7	47	25	44	0.05	0.98	38.9	85.3	20.3	Nilsson (1964)
61.6.2	1961	8	46	26	40	0.06	0.96	33.4	85.5	23.0	Nilsson (1964)
BF66	–	52	36	26	38	0.094	0.93	31.3	73.7	27.0	Baker and Forti (1966)
606	1969	32	49	23	41	0.08	0.96	17.4	81.7	28.0	Gartrell and Elford (1975)
Mean	2001–2003		43.0	26.4	39.4	0.0928	0.944	28.2	78.5	29.4	Campbell-Brown (2004)

¹Radiant: α : right ascension, δ : declination (in degrees) (J2000.0) V/g : velocity of diurnal aberration and zenithal attraction. (in km s^{-1}).
²Orbit: q : perihelion distance (in AU), e : eccentricity, i : inclination of the orbit (in degrees) Ω : longitude of the ascending node (in degrees), ω : argument of perihelion (in degrees).
³Numbers of the Arietid meteors.

small difference in the velocities (1.1 km s^{-1} , 0.3%) causes significant difference in the inclinations (5°) Table III.

Figures 1 and 2 display radiant distributions. Results from the past radar observations are overplotted in the same figure. The dashed line (Radar observation mean) shows the mean daily motion of the radiant from the past radar observations. Daily motion of the radiant (linear approximation) between the end of May and the middle of June observed in 2001–2003 are also plotted (Campbell-Brown, 2004). About the position and the daily motion of the radiant in right ascension, the results from our TV observations agree very well with the past radar observations and Campbell-Brown (2004). However, the radiant position in declination from our TV observations are shifted towards the south compared with the results from Campbell-Brown, and closer to the past radar observations.

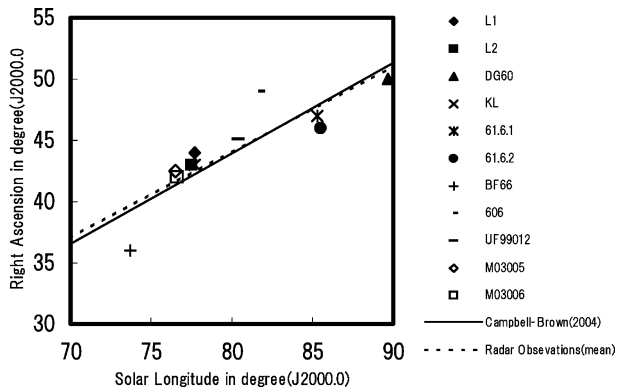


Figure 1. Right Ascension of the radiant of Arietids.

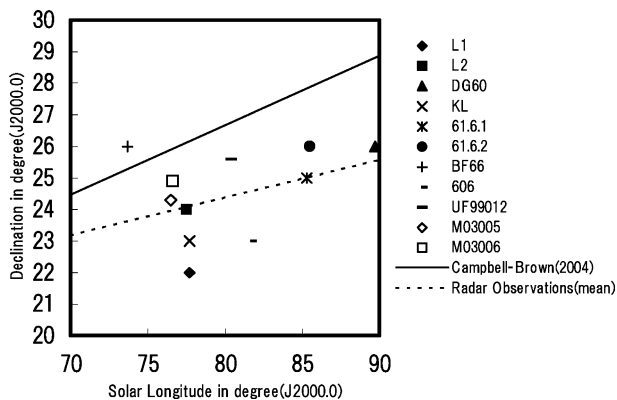


Figure 2. Declination of the Radiant of Arietids.

Variance of the declination of the radiant is larger than that of the right ascension, from the past radar observations. However, we cannot conclude this point from our observation of the small number of data. Further observations by TV instruments are desired.

4. Summary

We have successfully obtained precise orbits of Arietid meteors for the first time from a simultaneous TV observations. The orbits are similar to those reported by the past radar observations. Further observations with the same technique will contribute to clarify the details of radiant and orbit distribution of the Arietid shower.

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TECHNIQUES FOR MEASURING RADAR METEOR SPEEDS

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Abstract. We compare the results from the application of four different methods to determine the speed of meteoroids from single station radar data. The methods used are the pre- t_0 amplitude, post- t_0 amplitude, pre- t_0 phase and the Fresnel transform (FT) methods. Speeds from the first three methods are compared to the FT method since, requiring the use of the entire records of both the amplitude and phase data, this method is the most accurate of the four.

Keywords: meteor, meteoroids, radar velocity

1. Introduction

For complete dynamical information of meteoroids it is essential to determine their atmospheric velocities. Radar techniques, though able to detect smaller meteoric particles, generally cannot achieve the same velocity accuracy as for photographic and image intensifier methods. However, using single station backscatter radars, there are several techniques for estimating the atmospheric scalar speed of a meteoroid along its trajectory from its echo characteristics. Measurement of this parameter is important for studies of the interaction of the ablating body with the atmosphere and also for determining astronomical information.

For a single site radar system employing transverse scattering geometry (see Figure 1 left), the measured speed of the meteoroid by the radar is a direct measure of the rate of creation of ionization near the radar reflection point. It is thus possible to obtain information about ionization efficiency and plasma initial radius as well as determining the radar echo height and the velocity distribution of Earth impacts. These can also be used to verify multi-station time-of-flight velocity measurements.

In this paper, we use the Advanced Meteor Orbit Radar (AMOR) in single station backscatter mode to investigate four different methods of estimating the scalar speed of a meteor in the atmosphere. Each method has an inherent accuracy limitation which largely depends upon the amount of data required by each method to determine the scalar speed.

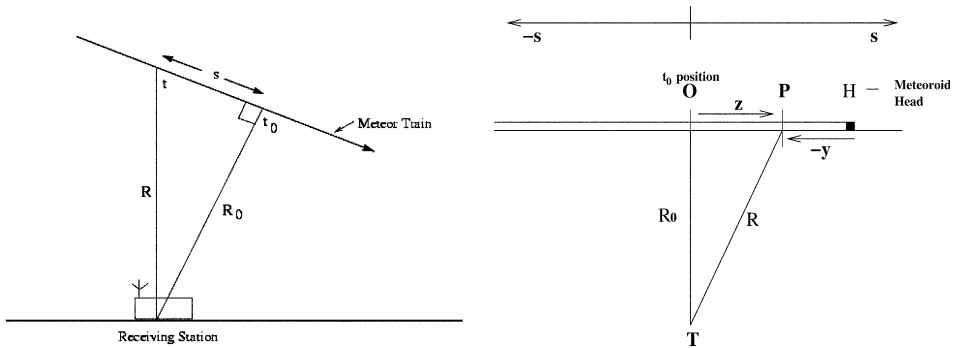


Figure 1. Left: The geometry for single station specular backscatter. Right: The geometry for Fresnel transform speed determination.

2. Background

The time variation of the scattering cross section of a meteoric plasma column can be described in terms of the generation of Fresnel intervals as the meteoroid progresses through the specular geometrical condition. The total scattered field – real part and phase behaviour can be conveniently expressed in terms of Fresnel Integrals C and S (see Figures 2 and 3 and for example McKinley, 1961 or more recently Baggaley, 2003).

There is a very convenient analogue between the generation of the meteor echo in the radar case and the optical case of diffraction at a straight edge, the complex diffraction characteristics being very usefully described by a Cornu spiral (Figure 3) with Fresnel parameter

$$x = \frac{2s}{(R_0\lambda)^{1/2}}$$

with s the physical distance travelled by the meteoroid.

As the meteor approaches the geometrically orthogonal condition $x = 0$ (designated the t_0 point) there is a rapid increase of the signal power as an increasing number of half-period Fresnel intervals contribute to the reflected radiowave energy. The phase increases monotonically reaching a maximum of close to $-\pi/6$ (actually -29.4°) at $x = 0.572$ (defining the phase as $-\pi/4$ when $x = 0$). The instant of maximum echo power occurs at $x = 1.217$.

The meteoric plasma column is free to move in the ambient atmosphere so that any local wind field will transport the plasma and introduce a phase gradient on the electric field and in consequence on the body echo signal. For any echo this plasma transport phase effect can be recovered from the post- t_0

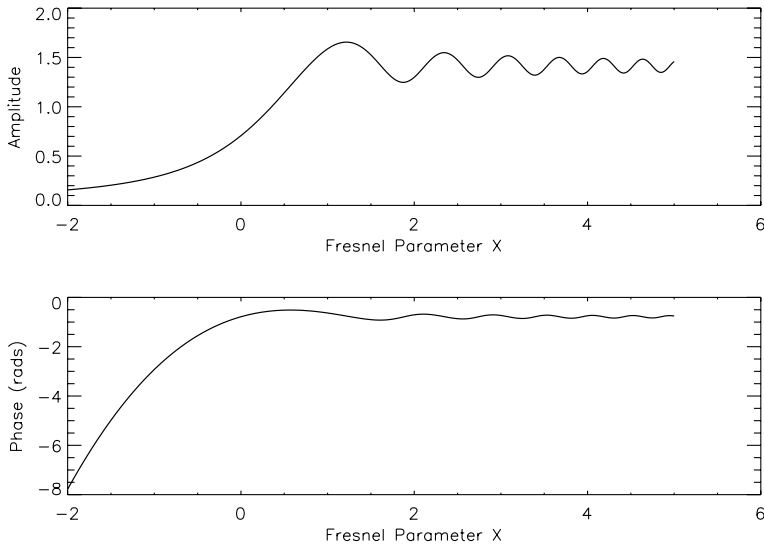


Figure 2. For the case of no diffusion. Top: Theoretical amplitude as a function of time. Bottom: Theoretical phase as a function of time.

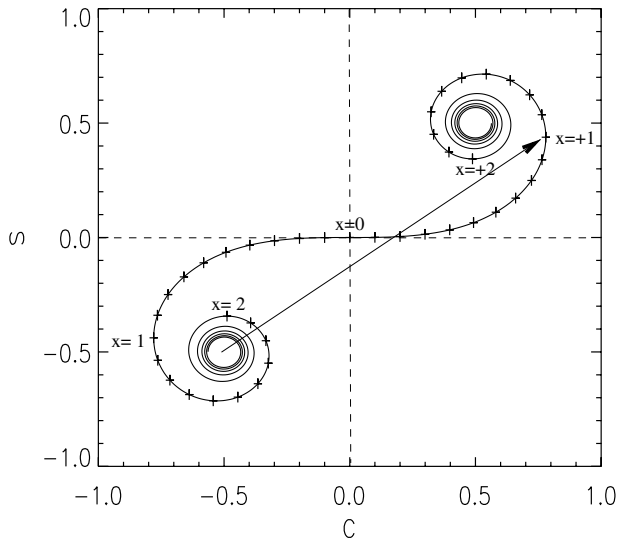


Figure 3. Modelled Cornu spiral with no diffusion. The amplitude vector at $x = +1$ is shown.

phase behaviour. In the following we note that this atmospheric phase modification has been taken into account.

Although the AMOR facility is a multi-station radar which is capable of determining meteor velocity components through a time-of-flight analysis,

we here confine our attention to estimating the meteor scalar speed using the radar in single station backscatter mode.

3. Determining the Meteor Speed

For a single-station radar system there can be four methods of determining radar speed of an individual meteor.

3.1. PRE- t_0 AMPLITUDE

To use the scattering cross section change prior to echo maximum, data corresponding to the echo amplitude function before the t_0 point is analysed. We require to quantify the magnitude of the amplitude increase over the Fresnel intervals prior to echo maximum. This corresponds to a Fresnel range of approximately $x = -2$ to $x = +1.217$. A full functional fit employing the entire amplitude response inclusive of noise should be used but, for illustration, a reasonable estimate of the speed (V_r 'rise-time speed') can be obtained over the time interval from $1/e$ amplitude to echo maximum τ and is given by

$$V_r = \frac{1.35(R_0\lambda)^{1/2}}{2\tau}$$

3.2. POST- t_0 AMPLITUDE

We consider the change in scattering cross section after the echo maximum. Subsequent to this maximum, the meteoroid traversal of Fresnel intervals is characterised by amplitude oscillations which correspond to diffraction. Because of ambipolar diffusion, turbulence and fragmentation, the plasma train can provide non-ideal scattering yielding distorted patterns. Under these conditions, the echo amplitude (and phase) behaviour may not in some cases provide useful signatures.

The functional form of the theoretical echo amplitude beyond the t_0 point is shown in Figure 2 for the ideal case of no diffusion. Diffusion effects dictate (see for example Simek, 1969; Pecina, 1996) that a better measure is to take the first minimum in the amplitude. Subsequent minima and maxima are given in Table I.

For large values of oscillating cycles h , maxima and minima are given by $[(4h-1)/2]^{0.5}$; with h being an integer ≥ 1 . If Δt is the time between minima n and m then the corresponding diffraction speed V_d is given by

$$V_d = \frac{(R_0\lambda)^{1/2}(x_n - x_m)}{2\Delta t}$$

Using a least squares fit to the oscillatory pattern enables reasonable accuracy ($< 5\%$) to be obtained for patterns containing more than five full cycles.

3.3. PRE- t_0 PHASE

Analysis of the data which exhibits the phase characteristics prior to the t_0 point can be performed to determine speed. In particular, we are interested in the rapid increase of the phase as the meteoroid approaches the specular condition. Notice, for $x < -1$ the Fresnel integrals can be described by the Cauchy approximations:

$$S = -0.5 - \frac{1}{\pi x} \cos\left(\frac{\pi x^2}{2}\right) \quad \text{and} \quad C = -0.5 + \frac{1}{\pi x} \sin\left(\frac{\pi x^2}{2}\right)$$

The phase angle given by

$$\tan(\phi) = \frac{-0.5 - S}{-0.5 - C}$$

becomes for $x < -1$

$$\tan(\phi) = \frac{-1}{\tan\left(\frac{\pi x^2}{2}\right)}$$

yielding $\phi = \frac{\pi}{2}(x^2 + 1)$, so that with $s = Vt$ and Z the length of the first Fresnel zone $(R_0\lambda)^{1/2}/2$,

$$\phi = \frac{\pi}{2} \left(\frac{V^2 t^2}{Z^2} + 1 \right)$$

TABLE I
Fresnel maxima and minima values of Figure 1

Maxima	2.344	3.082	3.674	4.183	4.637	5.049
Minima	1.873	2.740	3.391	3.937	4.416	4.848

Excludes the first maximum at $x = 1.217$.

At $x = -1$ this expression overestimates the phase by 7% compared to the exact Fresnel function. The phase change is approximately proportional to the square of the time prior to the t_0 point so that a quadratic fit can be used over the interval $x < -1$: this approach has been used by Cervera et al., (1997) and Hocking (2000). More generally and over a larger data sequence, the full functional fit to the phase in terms of the Fresnel integrals C and S , as carried out in this paper, can provide a more accurate estimation of the meteor's speed V_p . Typically, the phase signal is well defined but this is not always true for the amplitude signal. In fact, it is often the case that coherent and well defined phase signals are recoverable under conditions where the amplitude component of the signal is unusable. The criterion for the amplitude part of the signal to be useful is that the signal to noise ratio should exceed 8 dB.

3.4. COMPLEX SIGNAL – PHASE AND AMPLITUDE

As a meteor train forms orthogonal to the radar beam the received echo can be considered to be a one dimensional Fresnel diffraction pattern produced by a moving source. In order to extract information about the structure of the ionisation distribution a form of Fresnel Transform (FT) can be applied to the signal data. This method, using in an elegant way all the available amplitude and phase data, was first introduced by Elford 2001.

3.4.1. *Fresnel transform theory*

Detection of a meteoroid trail by the transverse scattering radar AMOR relies upon orthogonality of the t_0 point. It is useful to summarise Elford (2001).

The geometry appropriate to obtaining a FT is as shown in Figure 1 right. The radar signal as a function of time from a meteor considered to have constant velocity V is given by

$$E(t) \propto \int_{-\infty}^s G(z) \exp(j2kR) dz \quad (1)$$

where R is the range of the meteoroid at position P and $G(z)$ is the reflection coefficient due to elements dz . Defining the reflection coefficient of an element dz at P with respect to the head of the meteor gives

$$E(t) \propto \int_{-\infty}^0 A(y) \exp \left[jk \frac{(s+y)^2}{R_0} \right] dy \quad (2)$$

where the geometrical approximation

$$R \approx R_0 + \frac{z^2}{2R_0}$$

for large R_0 , as well as the transformations

$$z = s + y \quad \text{and} \quad dy = dz$$

have been used. If we now write $E(t) = E(s/V) = E^*(X)$, and $A(y) = A^*(Y)$, where $X = s/\sigma$, $Y = y/\sigma$ and $\sigma = [\lambda R_0 / (4\pi)]^{1/2}$, (2) can be rewritten as

$$E^*(X) \propto \exp(j\frac{X^2}{2}) \int_{-\infty}^{\infty} f(Y) \exp(jXY) dY \quad (3)$$

where $f(Y) = A^*(Y)\exp(jY^2/2)$ and the fact that $A^*(Y)$ is zero for all $y > 0$ (to the right of the meteoroid head) enables us to put the upper boundary of the integral to ∞ .

By letting $F(X) = \int_{-\infty}^{\infty} f(Y) \exp(jXY) dY$ a Fourier integral is formed whose Fourier transform is

$$f(Y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(x) \exp(-jXY) dX$$

By substituting the expression for $f(Y)$ and rearranging (3) we now obtain the expression

$$A^*(Y) \propto \int_{-\infty}^{\infty} E^*(X) \exp\left[-j\frac{(X+Y)^2}{2}\right] dX$$

Replacing $A^*(Y)$ and $E^*(X)$ respectively with $A(y)$ and $E(t)$ gives

$$A(y) \propto \int_{-\infty}^{\infty} E(t) \exp\left[-j\frac{(X+Y)^2}{2}\right] dX \quad (4)$$

The quantity $A(y)$ denotes the scattering function with respect to the head of the meteoroid and is the quantity we wish to determine. The calculation has been described by Elford (2001) as a convolution of the received signal $E(t)$ and a weighting function which, considering that $s = Vt$, can be seen to be

dependent upon the speed of the meteoroid. Since the units of X are Fresnel zones, the expression is described as a *Fresnel transform*.

3.4.2. *Practical evaluation of the Fresnel transform*

Quantifying the right hand side of (4) must be done in terms of real and imaginary components. This is readily achievable since the received signal $E(t)$ from AMOR consists of both amplitude ($A(t)$) and phase ($\phi(t)$) components and can be expressed in the form

$$E(t) = A(t) \exp[-j\phi(t)]$$

3.4.3. *Visual analysis*

The evaluation must be carried out for different meteoroid speeds to give a series of complex scattering functions $A(v)$ whose amplitudes are examined individually to obtain the optimum velocity. An example showing such transforms is shown in Figure 4.

This example shows AMOR amplitude and phase data and the amplitudes of resultant FTs for meteoroid speeds ranging from 56 to 76 km s^{-1} in 5 km s^{-1} steps. It is clear from this example that the optimum velocity is close to 66 km s^{-1} , the transform amplitude at this speed having the largest negative slope. It is possible to visually inspect a range of FTs at a speed resolution of 0.1 km s^{-1} but in practice, this method of obtaining the meteoroid speed is computationally too slow.

3.4.4. *Automated software analysis*

To accelerate and automate the inspection process, the slope of the FT is “windowed” and its gradient evaluated at different velocities. The initial process is carried out at a resolution of 1 km s^{-1} in order to obtain a first approximation of the optimum velocity and thereafter at 0.1 km s^{-1} resolution to focus on a more accurate result.

Figure 5 shows the results of this process applied to the AMOR amplitude and phase data of Figure 4. Since AMOR employs three separate antenna arrays in an interferometer arrangement for elevation angle measurement, three independent amplitude–phase signals are available to provide a FT speed estimate. This results in three FTs being available for each speed estimate.

It can be seen from the left hand plots of Figure 5 that the optimum meteoroid speed is approximately 66 km s^{-1} . The right hand plots of Figure 5 show the result of further refinement to produce independent estimates of 66.3 km s^{-1} , 66.4 km s^{-1} and 66.5 km s^{-1} when data from the three

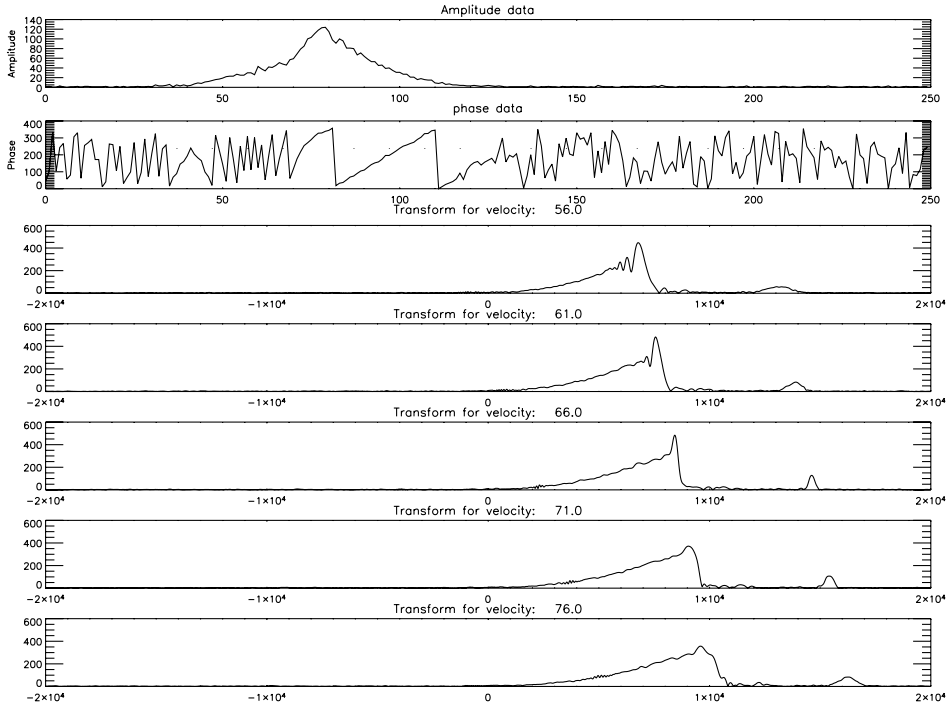


Figure 4. AMOR amplitude (top) and phase (second from top) data and their Fresnel transform amplitudes for speeds of 56.0, 61.0, 66.0, 71.0 and 76.0 km s⁻¹.

AMOR phase channels are combined with the amplitude data. This yields an estimated speed of 66.4 ± 0.1 km s⁻¹.

This automated approach to determining velocities from the gradient of FT amplitudes allows more rapid reduction of AMOR data.

4. Comparisons of Results

The methods described above are applied to data from the AMOR facility. This facility is capable of employing multi-station geometry to provide meteor trajectory velocity vectors but here we focus on using AMOR in the single station backscatter mode to provide a comparison of the above methods using a data set of 400 echoes.

Since the FT method uses more information, it has, in principle, the lowest uncertainty. We therefore present our data in a format where we represent the results for each of the three other methods as a function of FT speed.

The uncertainties for each method vary with the amount of data used. Generally speaking, the standard deviations from the residual data sets from

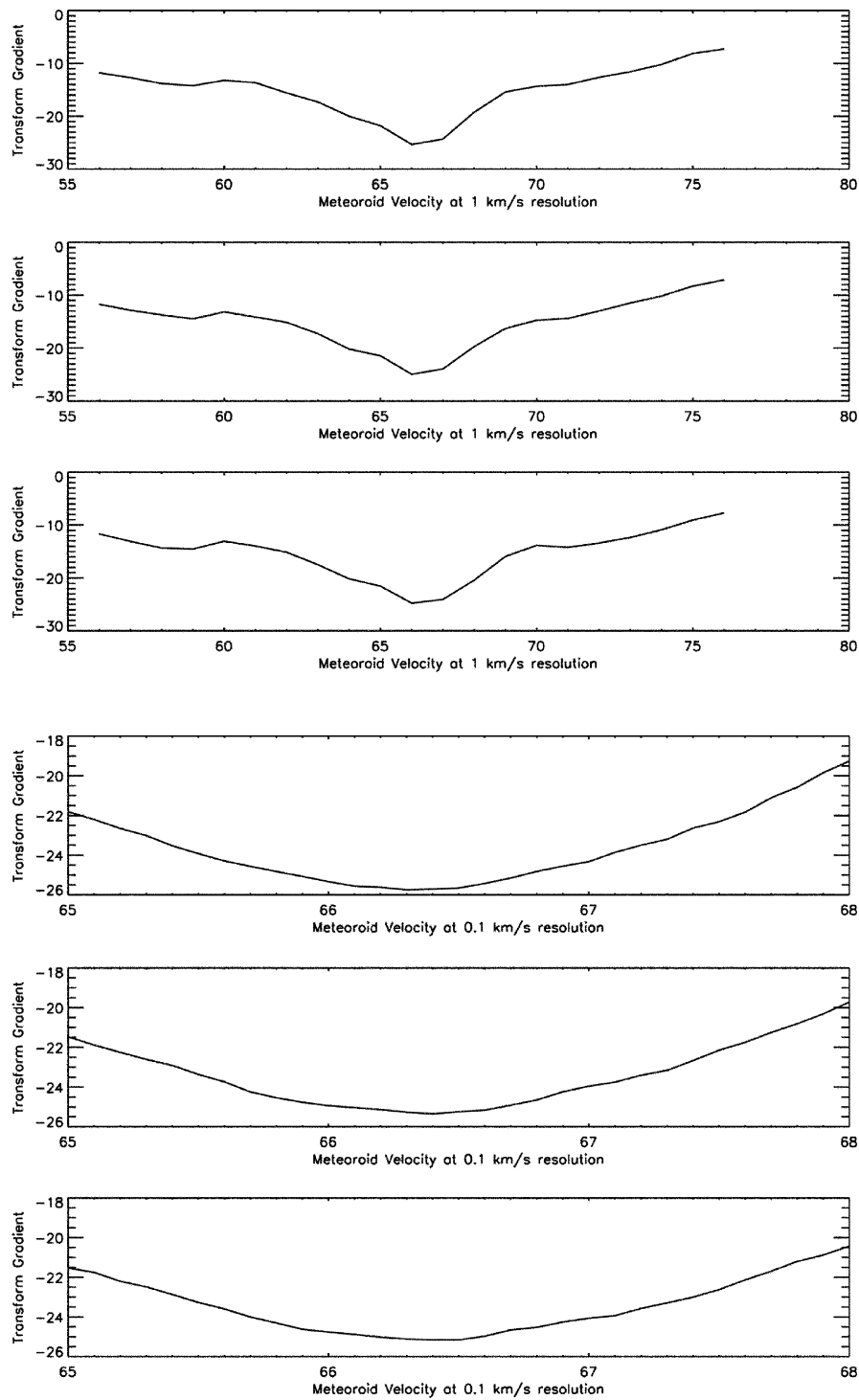


Figure 5. Determination of optimum velocity from the gradient of Fresnel transform amplitudes. Upper: For a resolution of 1 km s⁻¹. Lower: For a resolution of 0.1 km s⁻¹.

the pre- t_0 amplitude, the post- t_0 amplitude and the pre- t_0 phase methods are respectively 8.0, 1.1 and 1.1 km s⁻¹. From above, the uncertainty in the FT method is taken as 0.1 km s⁻¹.

Comparison of the pre- t_0 amplitude speeds to FT speeds (Figure 6) show the least agreement of all the methods being considered. Figure 6 (lower) indicates that this method generally overestimates speeds with the distribution of speed differences being mostly negative. However, examination of Figure 6 (upper) shows that for faster speeds the pre- t_0 amplitude method tends to underestimate many of the speeds.

The indications are that the post- t_0 amplitude method provides a relatively accurate method of determining meteoroid speeds with the distribution of speed differences being centred close to zero (Figure 7 lower). Its major limitation, however, is that there are relatively few echoes with a sufficient number of diffraction pattern oscillations to enable the method to be used.

The pre- t_0 phase method is both relatively accurate and provides a sufficient number of echos to justify its widespread use. Figure 8 (lower) indicates that the distribution of speed differences is both centred around zero and that a large number of pre- t_0 phase estimated speeds are very close to their equivalent FT estimated speeds with relatively few outliers being present.

5. Discussion and Conclusions

Rise time speeds can be obtained from single station meteor radar systems that have no phase measurement capability. They can typically make estimates of meteor speed that are good to an approximate uncertainty of 12%. This is useful where either a broad astronomical description measure is required or where an approximate speed value is required as an *a priori* estimate for use in another method. The FT method, for example, has been shown to entail much computing time as initial searches over a wide range of speeds are processed. This however, can be reduced by using initial estimate rise time speeds.

Although the post- t_0 amplitude method provides speeds which are in close agreement with FT speeds, accurate estimates are only possible for approximately 5% of all echoes. That is not to say that the remaining 95% of such echoes are not useful for other purposes. Such echoes can provide useful estimates of other atmospheric parameters such as diffusion and can also provide information about whether the meteoroid is underdense or overdense.

The pre- t_0 phase determination of speeds not only gives a good estimate of meteoroid speed but can also be used to determine the radial component of the background wind speed.

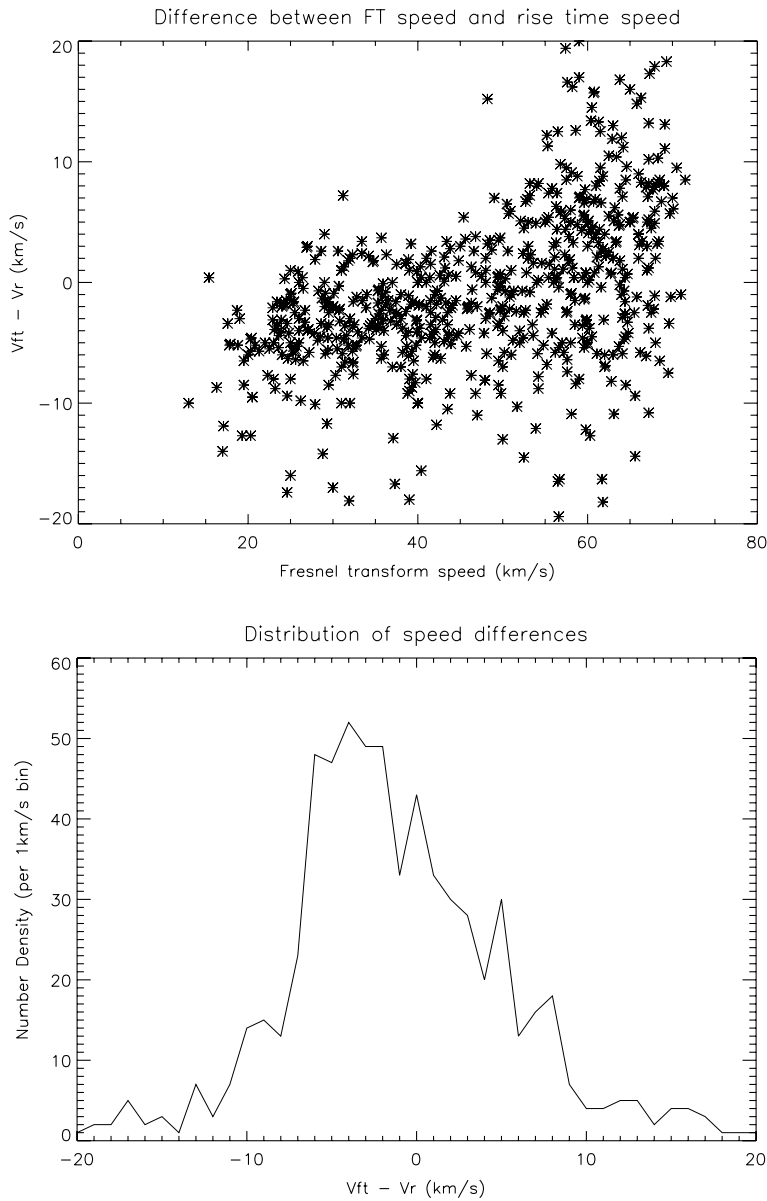


Figure 6. Upper: Comparison of rise time speeds with Fresnel transform speeds. Lower: Distribution of speed difference for this comparison.

The FT method of speed determination not only provides a good method to be used for comparing pre- t_0 phase speeds but is also valuable for verifying time-of-flight measurements when AMOR is used in multi-station mode.

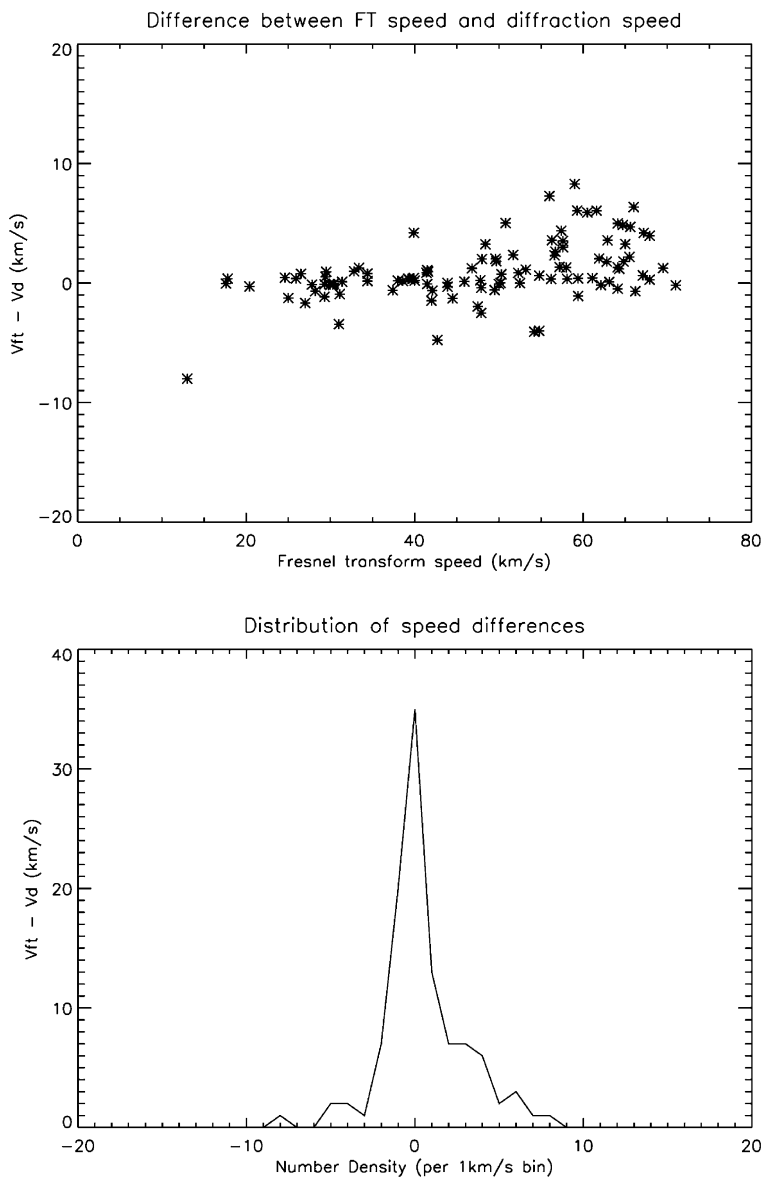


Figure 7. Upper: Comparison of post- t_0 diffraction speeds with Fresnel transform speeds. Lower: Distribution of speed differences for this comparison.

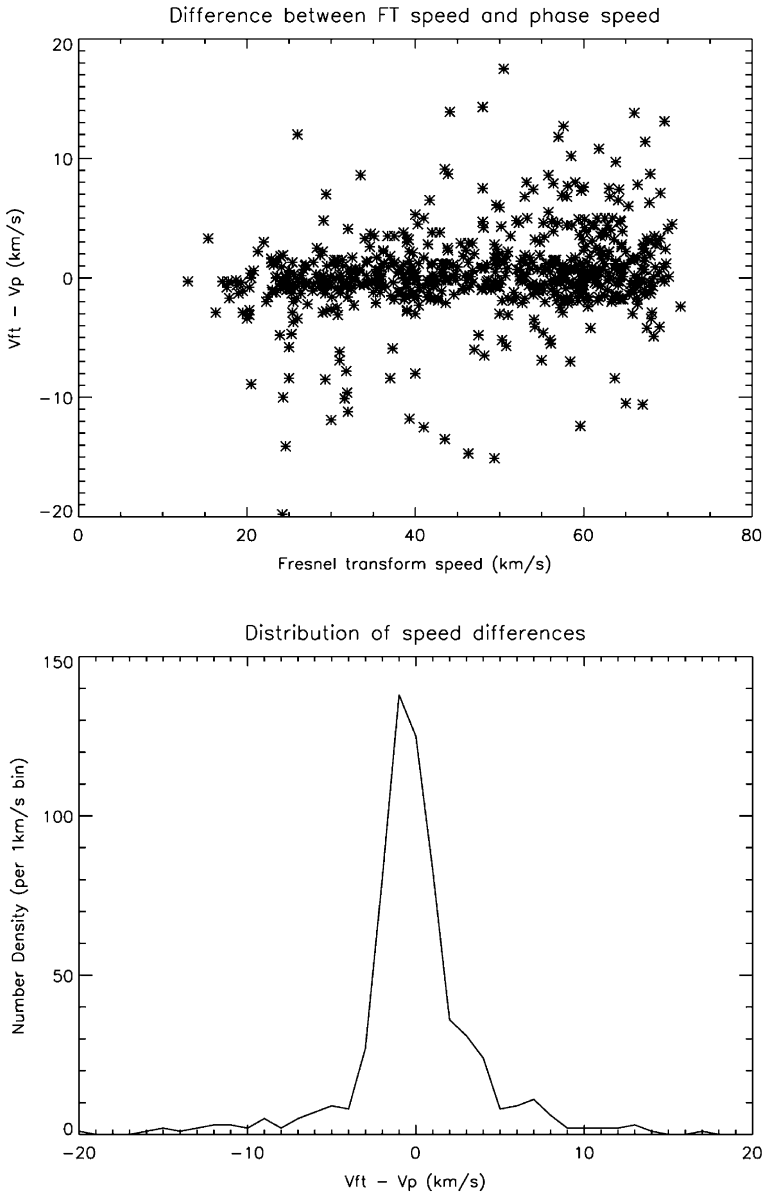


Figure 8. Upper: Comparison of pre- t_0 phase speeds with Fresnel transform speeds. Lower: Distribution of speed differences for this comparison.

Acknowledgement

To Graham Elford who pioneered the FT method and for fruitful discussions.

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THE VELOCITY DISTRIBUTION OF METEORIODS AT THE EARTH AS MEASURED BY THE CANADIAN METEOR ORBIT RADAR (CMOR)

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Abstract. The velocity distribution of meteoroids at the Earth is measured using a time-of-flight measurement technique applied to data collected by the CMOR radar (29.85 MHz). Comparison to earlier velocity measurements from the Harvard Radio Meteor Project suggests that HRMP suffered from biases which underestimated the number of fragmenting meteoroids. This bias results in a systematic underestimation of the numbers of higher velocity meteoroids. Other works (cf. Taylor and Elford, 1998) have also found additional biases in the HRMP which suggest the original HRMP meteoroid velocity analysis may have underestimated the fraction of high velocity meteors by factors up to 10^4 .

Keywords: meteoroid, radar, velocity distribution

1. Introduction

An accurate measure of the velocity distribution of meteoroids at the Earth is important for addressing a number of critical questions in meteor astronomy. The origin of various meteoroid populations is related intrinsically to their observed velocity at the Earth. All retrograde particles, for example, must have observed velocities in excess of approximately 32 km s^{-1} (with a variation of $\sim 0.5 \text{ km s}^{-1}$ during the year due to the non-zero eccentricity of the Earth's orbit) and these are all related to comets. The meteoroid velocity distribution is central to interpreting the distribution of micro-craters on the moon, the height deposition of meteoric metal atoms in the upper atmosphere, the total meteoroid mass influx to the Earth and crucial to engineering estimates of the meteoroid impact hazard to satellites orbiting the Earth.

The meteoroid velocity distribution at the Earth has been previously measured using photographic and radar techniques. Erickson (1968) used a random sample of Super-Schmidt data to estimate the true velocity distribution of sporadic meteoroids to a constant limiting mass at the top of Earth's atmosphere. The primary limitation of his work was the small

number statistics involved (286 sporadic meteors) and the lack of daytime coverage. The Harvard Radio Meteor Project (HRMP) has become the other source of meteoroid velocity information at the Earth (cf. Sekanina and Southworth, 1975). Recently, Taylor (1995) re-examined the HRMP velocities and found several errors in the original analysis. One result of these recent corrections was to increase the number of higher velocity meteoroids ($v > 60 \text{ km s}^{-1}$) by as much as two orders of magnitude. However, the HRMP data suffer from additional biases not accounted for in the Taylor (1995) re-analysis including the effects of fragmentation, Faraday rotation attenuation (cf. Ceplecha et al., 1998) and unequal diurnal coverage, though some of these and other effects were taken into account by the analysis of Taylor and Elford (1998). In particular, the use of the Fresnel oscillations in signal amplitude to measure the velocities for HRMP and the requirement that at least three complete Fresnel oscillation cycles from three stations be visible before a velocity measure is made (Hawkins et al., 1964) produce a severe bias. Since fragmentation causes much smearing of the individual Fresnel cycles, such a restriction will almost completely eliminate meteoroids which fragment.

Here we have attempted to measure the true out-of-atmosphere velocity distribution of meteoroids encountering the Earth using the Canadian Meteor Orbit Radar (CMOR). Details of the radar system hardware, analysis software and system operation are given in Jones et al. (2004) and Hocking et al. (2001). This analysis represents our preliminary estimate of the velocity distribution using all calibrations and bias corrections presently available. We expect to make another revision to this work once additional calibration data (particularly simultaneous optical – radar observations and a revision of the initial trail radius correction) are gathered. Another recent velocity analysis based on extensive radar data gathered by the Advanced Meteor Orbit Radar (AMOR) presented by Galligan and Baggaley (2004) has found similar general conclusions to the present work.

2. Data Selection, Corrections and Analysis

Velocity data from CMOR using time-of-flight (tof) measurements from three stations collected from May, 2002 to September, 2004 were used in the present study. A total of 1.5 million echoes with tof velocities were selected initially for this survey. From this initial population only echoes with radiants north of the ecliptic plane were retained to avoid large corrections that must be applied when dealing with deep southern radiants which have small integrated daily collecting areas. This restricts our analysis to only meteoroids with descending nodes at the Earth. The assumption is made that the velocity distribution is symmetric with respect to ecliptic plane.

Computing the true out-of-atmosphere velocity for each echo requires an estimate of the deceleration which has occurred in the atmosphere. To perform this correction, we examined 13 showers visible with CMOR having previously well-measured geocentric velocities from photographic or video techniques since early portions of the shower meteor trail (where deceleration is least) can be used and/or decelerations directly measured. Examining those meteors associated with each shower, a generally linear trend in apparent velocity vs. height was noted. That is, shower members observed at lower heights had (on average) lower velocities than those at higher heights, as would be expected. Using data for each of the 13 showers, combined from all years in which each shower was observed by CMOR, a linear fit of the observed geocentric velocity vs. height per shower was constructed. Comparing this fit to the accepted geocentric velocity of the shower, an estimate of the height at which no measurable deceleration occurs per shower (i.e. where the observed geocentric velocity equals the literature value) and the loss of speed at that height is made. Figures 1 and 2 show the resulting fits. By combining data from all 13 showers used in this way, a single velocity correction factor was found of the form:

$$\Delta V_{obs} = -((-0.0050098V_{obs} + 0.5142)(h - (0.3362V_{obs} + 86.6039))) \quad (1)$$

where ΔV_{obs} is the expected change in the apparent velocity (in km s^{-1}) for an echo observed at a height h (in km). Note that this deceleration applies specifically to the CMOR system (29.85 MHz) and its range of observed

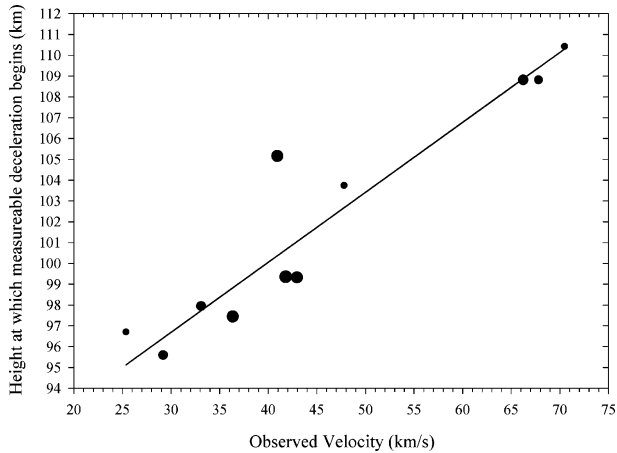


Figure 1. The apparent height at which noticeable deceleration begins for 13 different showers measured by CMOR. Apparent height is defined as the height at which the best fit line of measured velocity vs. height intersects the accepted out-of-atmosphere velocity for the shower. The size of each point is proportional to the log of the number of echoes used in the distribution to determine the intersection height. The solid line is the number weighted least-squares best fit.

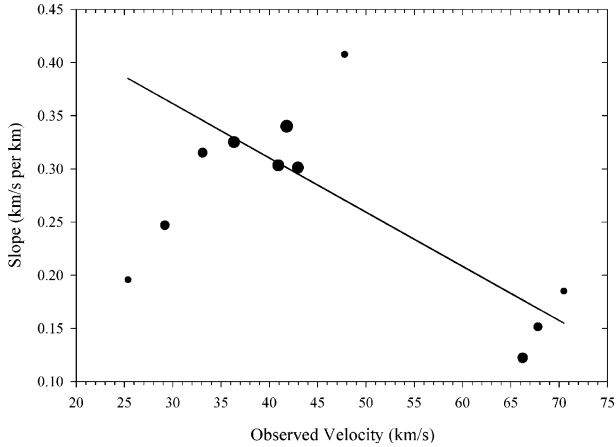


Figure 2. The slope of the change in deceleration as a function of measured velocity for 13 major showers observed by CMOR. The symbol sizes and line have the same meaning as in figure 1.

masses with height. Other systems with different sensitivity limits and different wavelengths would not necessarily see the same behaviour. We have also examined the dependence of entry angle on velocity – this shows a much smaller correlation with decelerations in the population as a whole noticeable only at low ($< 20^\circ$) radiant elevations. We have thus ignored this correction. Note that when Equation (1) becomes positive (which would signify an increase in speed), we set ΔV_{obs} to zero, following figure 1. The average correction varies from about 1 km s^{-1} at the lowest observed velocities to nearly 2.5 km s^{-1} at a velocity of 50 km s^{-1} . Thus this correction is comparable to or smaller than the mean error in speeds ($\sim 5\%$) at lower velocities, but nearly negligible relative to the error spread in speeds at higher velocities.

In addition to correcting for deceleration, each observed echo is inversely weighted according to the daily integrated collecting area appropriate to its apparent radiant. Details of the procedure for computing collecting area can be found in Brown and Jones (1995). For northern ecliptic radiants, the integrated daily collecting area varies between the limits 1500 km^2 to 5500 km^2 .

Finally, each echo is inversely weighted according to the attenuation in signal amplitude produced by four different effects: initial trail radius, interpulse period detectability, diffusion due to finite velocity and Faraday rotation of the radio wave. Details of these effects and the numerical expressions used to quantify the degree of attenuation can be found in Cepelcha et al. (1998) and Cervera et al. (2004). For readers not familiar with these effects we will briefly and qualitatively describe each.

The initial trail radius effect is arguably the most important effect and also the most difficult to quantify (cf. Cepelcha et al., 1998). This effect results in

an attenuated signal amplitude when the physical radius of the meteor trail exceeds $\lambda/2\pi$, where λ is the radar wavelength. Classically, this radius has been assumed to be limited by the thermalization scale of ablated atoms, however more recently it has become clear that the effect is probably dominated by fragmentation effects (Campbell-Brown and Jones, 2003; Cervera and Elford, 2004). Still a poorly constrained effect, we adopt the radius dependence of Cervera and Elford, (2004) and compute the attenuation assuming a Gaussian distribution of electrons across the trail (cf. Cervera and Elford, 2004 for more details). The initial trail radius effect remains the most serious shortcoming of the present analysis; once a more complete description of the effects of initial fragmentation radius is known, this analysis should be redone.

The inter-pulse period attenuation reflects the fact that a trail which diffuses to $\lambda/2\pi$ in a time which is short compared to the time between radar samples will be strongly biased against detection. For CMOR, detection occurs if a potential echo remains above the background for more than four consecutive samples. Echoes with decay times less than ~ 0.01 sec will not be readily detected.

For meteoroids moving at slower velocities, the time to cross the central Fresnel zone (where almost all of the backscatter signal arises) may be longer than the diffusion timescale at that height. In such cases, the fact that the meteor has a finite velocity in crossing the central Fresnel zone will lead to decreasing contributions to the scattered signal from those portions of the trajectory earlier in flight. This results in a reduced signal amplitude at the receiver in comparison to the case where the meteor velocity is neglected (i.e. the meteor is treated as though it has an infinite velocity).

Finally, linearly polarized radio waves propagating in a magnetized plasma experience a rotation in their plane of polarization (cf. Cepelcha et al., 1998). As rotation of the radio wave occurs, the returned signal will be attenuated, with essentially no signal detected if rotations of 90° or 270° occur between transmission and reception. As CMOR uses linear dipole type antennae for both receiving and transmitting this is a potential source of echo attenuation. The magnitude of the rotation depends (among other things) on the electron content of the ionosphere. At CMOR's frequency there is almost no Faraday rotation during nighttime hours. However, the effect of Faraday rotation can be important for CMOR echoes over an altitude of ~ 95 km during daytime ionospheric conditions. Here we adopt the International Reference Ionosphere – 2000 (IRI) model (Bilitza, 2000) and use it to provide the electron content along each transmit – receive echo path and measure the expected attenuation for each observed echo.

All four of these attenuations are multiplied together and each velocity measure is then weighted by the inverse of the product. Echoes which have total attenuations of more than 100 are removed from the analysis.

Finally, to produce a velocity distribution for a single mass limit, we follow the procedure outlined in Taylor (1995) which was used to correct the HRMP data. In this approach, all echo masses are referenced to the equivalent limiting threshold mass at 30 km s^{-1} , which for CMOR is approximately $4 \times 10^{-7} \text{ kg}$. We have also adopted the same constants used in Taylor's re-analysis of HRMP for the cumulative mass distribution index ($\alpha = 1.36$) and for the ionization production exponent of $\gamma = 4.25$ (i.e. ionization $\propto m^{0.92} v^{3.91}$ with $\gamma = 3.91/0.92 = 4.25$). Thus the cumulative number of meteoroids with mass greater than the threshold mass of $4 \times 10^{-7} \text{ kg}$ at 30 km s^{-1} (m_{30}) as a function of velocity is given by:

$$N(m > m_{30}) = \left(\frac{v}{30}\right)^{-\alpha\gamma} N(m > m_v) \quad (2)$$

relative to the number measured in velocity bin v (see Taylor (1995) equation 6). Physically, this weighting accounts for the fact that faster meteoroids produce more ionization per unit mass, the radar being more sensitive to smaller, fast meteoroids and seeing "deeper" into the distribution of small particles at higher velocities.

3. Results and Discussion

To understand the connection between the original HRMP results and our data, we first attempt to reproduce the results from HRMP. One advantage of this comparison is that both stations are at nearly the same latitude (HRMP 40N, CMOR 43N) and both have similar limiting mass thresholds (10^{-4} g for data used in the HRMP velocity survey and 10^{-5} g for CMOR). As stated earlier, we suspect that the technique used to measure velocities by HRMP (Fresnel oscillations) suffers from a hidden bias in that heavily fragmenting meteoroids will not be selected for measurement due to the strict selection criteria applied to the original HRMP data. Such echoes will be detected by the system, but the Fresnel oscillations will be "smeared" out by the presence of multiple, overlapping Fresnel patterns from different fragments in the vicinity of the main trail. From general physical considerations, we may expect that cometary meteoroids would be more prone to such fragmentation, so we would expect the greatest underestimation to occur at the highest velocities where high inclination/cometary meteoroids predominate.

To test this notion, we make use of a hybrid-Fresnel velocity measurement technique introduced by Hocking (2000). This velocity technique uses Fresnel oscillations in both amplitude and phase and determines the speed using a Fourier transform approach. The selection criteria applied by this technique

is such that only 5% of all detected CMOR echoes have sufficiently “clean” Fresnel oscillations to permit measurement. For comparison, $\sim 1\%$ of all echoes detected by HRMP met all selection criteria and were used in their final velocity analysis (Lacy, 1966; Cook et al., 1972). While it is not possible to know the exact correspondence between the different selection procedures applied by each algorithm, the fact that only a small fraction of all echoes are accepted for reduction in both cases and that both rely on the presence of Fresnel oscillations for measurements should render the two at least qualitatively similar. Figure 3 shows the velocity distribution for HRMP as given by Taylor (1995) and the velocity distribution produced from 7.5×10^4 echoes analysed from CMOR using the hybrid-Fresnel technique. Both distributions have been normalized to the number of echoes in the 20 km s^{-1} bin. The general shape and relative proportion of echoes is very similar for both distributions across the velocity range shown. The only major deviations are at the lowest velocities ($<18 \text{ km s}^{-1}$), where the number of echoes detected by the CMOR hybrid-Fresnel is ~ 2 times less than the HRMP numbers and at the highest velocities where CMOR is almost a factor of five above HRMP values. It is worth noting that the number of echoes in the HRMP survey with velocity above 65 km s^{-1} is less than 100 (Sekanina and Southworth, 1975), so the statistics at the high end of the range are very poor. For comparison, over 3000 echoes with velocities above 65 km s^{-1} had hybrid-Fresnel velocity measurements from CMOR. It is also important to recognize that the Fresnel method begins breaking down at the very highest speeds due to inadequate sampling of the Fresnel cycles between successive pulses. This may be another explanation for the under-representation of higher velocity echoes.

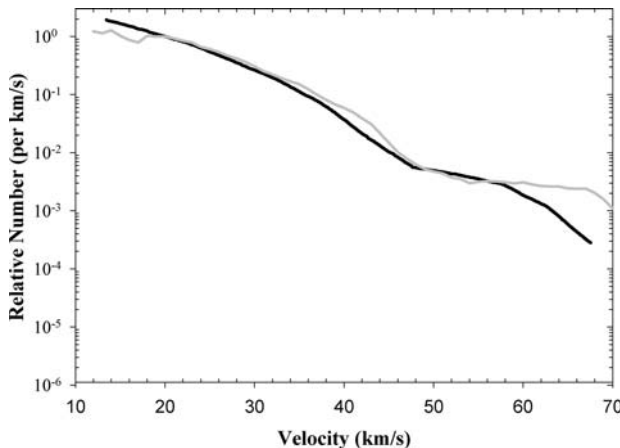


Figure 3. The relative number of meteoroids as a function of velocity for HRMP (solid black line) and CMOR measured using the hybrid Fresnel technique (gray line). Both distributions are normalized to the 20 km s^{-1} velocity bin.

Having established that the Fresnel technique is inherently biased against high velocity meteors and showing that we can reproduce its general shape, we examine the HRMP distribution in comparison to the complete CMOR distribution using the tof velocity measurements in Figure 4. Also shown is the photographically measured velocity distribution for larger (mass $\sim 1\text{g}$) meteors in the Erickson (1968) sample. The main feature is the systematically higher number of meteors with velocities $> 40\text{ km s}^{-1}$ in the CMOR sample compared to HRMP from Taylor (1995). This reaches more than an order of magnitude difference in the $60\text{ to }70\text{ km s}^{-1}$ velocity range. We also note that the more recent HRMP velocity distribution corrected according to the methodology in Taylor and Elford (1998) (their Figure 3) shows a small increase for speeds in excess of 45 km s^{-1} , giving a “knee” at $45\text{--}50\text{ km s}^{-1}$ as is also evident in the CMOR and Erickson distributions.

The implication is that the numbers of cometary meteoroids in the original HRMP survey were underestimated, perhaps by as much as an order of magnitude. Interestingly, the Super-Schmidt data, with much poorer statistics agree on the relative numbers of very fast meteors in comparison with CMOR, though the numbers of medium velocity particles are generally lower throughout the entire Erickson (1968) distribution.

4. Conclusions

The velocity distribution of meteoroids at the Earth as given by the HRMP survey underestimates the contribution from high velocity, fragmenting

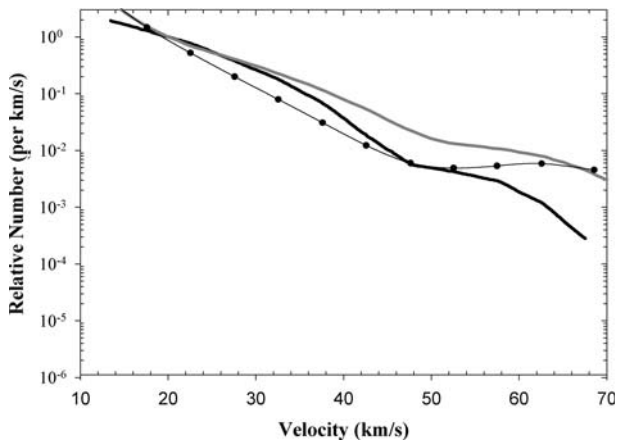


Figure 4. HRMP velocity distribution (black line), the CMOR time-of-flight velocity distribution (gray line) and the photographically determined velocity distribution from Erickson (1968) (solid circles with thin line). All distributions are normalized to the number of meteors in the 20 km s^{-1} bin.

cometary meteoroids as compared to measurements from the CMOR survey which uses a different velocity measurement technique (time-of-flight). More recent measurements (Baggaley, 1998) suggest that the cumulative mass distribution index is closer $\alpha = 1.0$ and hence that the value used in the HRMP analysis may have been too high. A change to smaller mass indices will further increase the true proportion of faster meteoroids.

The change in ionization efficiency with velocity remains poorly constrained at higher velocities as does the true effect of initial fragmentation radius on echo attenuation. As these two effects are better quantified, a re-analysis of the velocity distribution would be warranted.

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THE HYPERTHERMAL IONIZATION AND HIGH ABSOLUTE METEOR VELOCITIES OBSERVED WITH HPLA RADARS

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Abstract. High Power Large Aperture (HPLA) radars generally observe very high meteor velocities averaging over 50 km s^{-1} . There are only a few events recorded around 30 km s^{-1} , while meteors at 20 km s^{-1} or slower are very rare. This is a clear and debated contradiction to specular meteor radar results. A high plasma density condition contributes, but the dominating phenomenon is the hyperthermal ionization mechanism due to chemical dynamics of the ionization process. The observed high velocities can be explained in terms of high hyperthermal ionization cross-sections for collisions between ablated meteoroid metal atoms such as Na and/or Fe and atmospheric species.

Keywords: HPLA, hyperthermal ionization, meteors, velocities

1. Introduction

High power large aperture (HPLA) radars monitor meteor flux primarily through the detection of head echoes. The scattering process behind these observations is assumed to be scattering from the plasma created in the vicinity of the meteoroid due to its interaction with the atmosphere (Wannberg et al., 1996; Close et al., 2002a, b; Hunt et al., 2004). Submillimeter size meteoroids are assumed in this study in agreement with observations with EISCAT UHF (931 MHz) and VHF (224 MHz) radars (Pellinen-Wannberg et al., 1998).

The velocity of a meteoroid is an important parameter in meteor astronomy and it can be measured with both HPLA radars and specular meteor radars. The latter radars observe meteors when the trail is orthogonal to the radar beam and about 90% of the received echo power comes from the central Fresnel zone symmetrically located about the orthogonal point on the trail. For these meteor radars operating at frequencies of 30–50 MHz, the

effective coherent scattering region has a length of about 1 km. Speeds are determined from measurements of the phase of the echo during the formation of the trail behind the ablating meteoroid which moves along a highly linear path in the atmosphere. Except for the effect of a small deceleration (although relatively large in the terminal region of the trail) most speeds measured with meteor trail radars are close to the 'no-atmosphere' speed of the meteoroid.

Speeds of sporadic meteors observed with specular meteor radars range from 10 to 70 km s⁻¹. The distribution of the speeds has a broad maximum between 30 and 50 km s⁻¹, but the actual form of the distribution is very significantly affected by astronomical and observational selection effects, the predominant one being the presence or absence within the beam of particular broad radiant sources such as the helion, anti-helion and apex sources (Jones and Brown, 1993). Correction for the selection effects dramatically changes the speed distributions of meteoroids that give rise to meteor trails observed by radar (Hunt et al., 2004).

HPLA radars observe velocities in a different way. The Doppler shifts or time-of-flight estimates from the non-specular head echoes give just the velocity component along the direction from the radar to the meteoroid. The HPLA radar beams are very narrow, a few degrees at most. Thus when pointing the radar beam vertically, only the geocentric velocity component distribution is obtained. There are, however, different ways of estimating the true vector velocities, by multistatic radars such as EISCAT UHF, with multiple feed horns as at ALTAIR or by phased array radars as in Jicamarca. Very high mean absolute velocities or speeds are reported – generally above 50 km s⁻¹; there are a few 30 km s⁻¹ meteors, while 20 km s⁻¹ meteors are very rare. In this report, we suggest that the bias toward the observation of high speeds is a result of the chemical dynamics of the ionization process. Our treatment complements two studies that were published recently, namely those by Close et al. (2004) and by Hunt et al. (2004).

2. Ionization, Scattering and Velocities

The plasma density condition for head echo scattering depends on the monitoring frequency. Thus the head echo altitude distributions vary for different radars. At EISCAT dual-frequency observations of the same meteors have been carried out and we have seen that at VHF the head echoes appear when the plasma generated in the interaction process reaches the 224 MHz critical density of $6 \times 10^{14} \text{ m}^{-3}$ for average conditions that corresponds to about 110 km altitude. A few kilometers further down, the plasma density will increase due to further ionization and compression of the interaction volume, so that even the critical density corresponding to

EISCAT UHF 931 MHz, $1 \times 10^{16} \text{ m}^{-3}$, is reached. At the same time the VHF echo is still observed. In dual-frequency observations of a common volume by EISCAT, every UHF meteor is also seen in VHF. These dual-frequency meteor head echo altitude distributions have recently been discussed by Westman et al. (2004), where a single-collision meteoroid-atmosphere interaction model was used to compute the condition for critical ionization as a function of meteoroid size, velocity, and neutral atmosphere density. In this model, free-molecular regime hypersonic interaction is assumed creating a very dense plasma in front of the meteoroid through single inelastic collisions with air molecules (the physical and chemical processes required for a full understanding of this phenomenon can be found in the monograph by Bronshten (1983)).

Figure 1 (adapted from Westman et al., 2004) shows, for a range of meteoroid sizes, curves that indicate the height at which the meteors first reach the required plasma density condition at EISCAT UHF and VHF. The three pairs of curves (starting at right with 72, 40, and 20 km s^{-1} initial velocities) show particles that are just below the limit size to reach the plasma

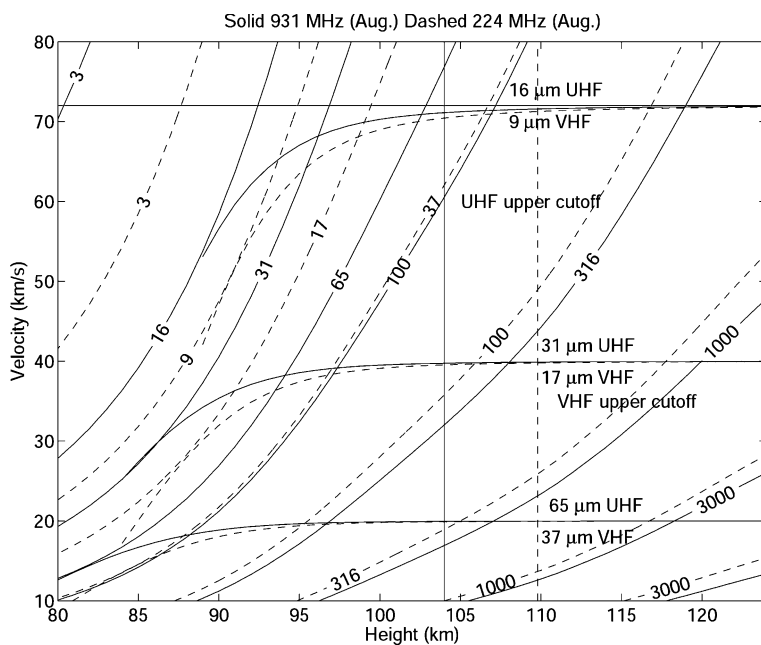
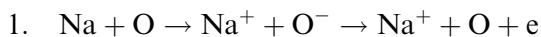


Figure 1. Plasma density condition curves. The condition for the required plasma density ionization due to combined meteoroid velocity-atmospheric density effect is reached above the curves labeled with particle radii in μm . The three pairs of curves (starting at right with 72, 40, and 20 km s^{-1} initial velocities) show particles that are just below the limit size to reach the plasma density condition when even the deceleration has been taken into account. The solid lines are for the 930 MHz UHF and the dashed for the 224 MHz VHF. The UHF and VHF upper cut-off lines show the altitude below which 90% of the head echoes are seen.

density condition when even the deceleration has been taken into account. Based purely on physical considerations, we can conclude that a strong interaction between the meteoroid and the atmosphere is required to generate observable head echoes. Still, within this physical model, 20 km s⁻¹ meteoroids larger than 65 μm radius for UHF or larger than 37 μm at VHF reach the required plasma density condition above 80 km altitude as the lowest velocity curves as shown in Figure 1. Such meteors would be observed if just the single-collision model was valid.

Hyperthermal collisions of the metal atoms with the atmospheric constituents, principally O and O₂, will lead to ionization directly:



The molecular details of these reactions are quite complex. However, there is a reasonable calculation of the cross-section of reaction (1) as a function of velocity, as shown in Figure 2, which is adapted from (Dressler and Murad, 2001). The cross-section which is ~1 Å² or 1 × 10⁻²⁰ m² close to 80 km s⁻¹ falls about one order of magnitude at 40 km s⁻¹ and decreases more rapidly below that. Data on other relevant reactions show similar features and will be discussed in an extended paper.

The hyperthermal collision cross-section emphasizes further the effect illustrated in Figure 1: that a proper combination of size, velocity, and atmospheric density is needed for threshold conditions to create head echo circumstances for a given frequency.

The absolute values of the vector velocities derived so far from 10 tri-static observations at EISCAT UHF average 64.7 km s⁻¹, while the lowest observed value was 38.7 km s⁻¹ (Janches et al., 2002). Close et al. (2002a) report absolute velocities of sporadic meteors down to 30 km s⁻¹, and that 20 km s⁻¹ sporadics can fall below the limiting capability of the radar. In fact, the hyperthermal ionization cross-section is two orders of magnitude less at 20 km s⁻¹ than at 30 km s⁻¹. Close et al. (2002b) also report absolute velocities averaging 52 km s⁻¹ at VHF and 65 km s⁻¹ at UHF. The results shown in Figure 2 are in qualitative agreement with those shown in Figure 4 of the paper by Hunt et al. (2004) based on the calculations by Jones (1997). It is worth noting, however, that Hunt et al. (2004) use the analysis of Jones (1997) for their plasma calculations, even though Jones (1997) states that his analysis is only valid for meteoroid velocities < 35 km s⁻¹. The molecular calculations given in Figure 2 are based on accurate molecular potentials for the Na–O system; necessary information is not available for the Fe–O or other metals. In fact, there are no experimental

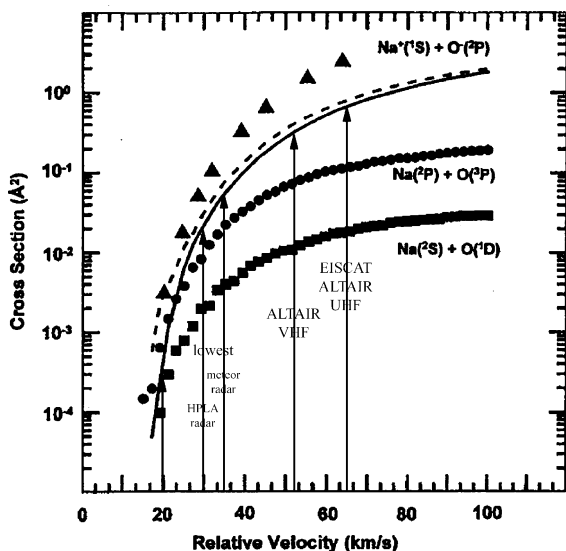


Figure 2. Cross-section dependence on velocity. The dependence of the collisional ionization cross-section (solid line) on collision velocity is shown. This cross-section was calculated using a multichannel Landau–Zener formalism, which is described in detail in (Dressler and Murad, 2001). The dotted lines are related to optical emissions. Also cross-section values are indicated for some velocities discussed.

measurements of the ionization cross-sections in collisions between atomic oxygen and metal atoms at hyperthermal energies.

More sensitive radars and lower frequencies are likely to observe slower or larger meteoroids. It is interesting to note, in passing, that Jones and Webster (1991) using a 33 MHz specular meteor trail radar, also observed an increasing number of head echoes with increasing meteoroid incoming velocity, the lowest being at 35 km s^{-1} .

3. Discussion

We note that Millman and McKinley (1963) report spectra of N_2^+ , Ca^+ , Mg^+ and Si^+ for Perseid meteors ($v \sim 59 \text{ km s}^{-1}$). In contrast, very slow meteors coming at low velocities showed emissions from neutral atoms only. Observed high vector velocities of meteoroids through head echoes from HPLA radars can be explained in terms of the large hyperthermal cross-sections for collisional ionization of typical ablated meteoroid metal atoms. The Na–O cross-section increases slowly above 40 km s^{-1} but decreases by three orders of magnitude in going from 40 to 20 km s^{-1} . This fact has several important implications for the use of the HPLA method for

meteor observations. The achieved instantaneous ionization depends on the meteoroid's size, density, and velocity and on atmospheric conditions at the time of entry. The observability of head echoes depends on the frequency and sensitivity (i.e. power and aperture) of the radar. It is impossible to state at this time what the numbers are for the different HPLA facilities in the world; in general, these radars are less sensitive for slow meteors than for fast meteors. This results in biases such as underestimates of total meteor rates and in up-shifted velocity distributions.

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POWER FLUCTUATIONS IN METEOR HEAD ECHOES OBSERVED WITH THE EISCAT VHF RADAR

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Abstract. We present observations and preliminary results from a meteor experiment carried out with the 224 MHz EISCAT VHF radar in Tromsø, Norway, which was run for 6 h on November 26, 2003. The data set contains echoes with peculiar pulsations in received power in the frequency range 20–200 Hz, limited by instrumental parameters. The process causing the echo power pulsations has not yet been identified. Plasma effects are the most likely cause, a possible mechanism is for instance asymmetrical dust grains in rotation causing a modulation of the ionization rate.

Keywords: HPLA radar, meteor head echo, meteoroid rotation, plasma effects

Abbreviations: EISCAT: European incoherent scatter; HPLA: high power large aperture; SNR: signal-to-noise ratio

1. Introduction

Several authors, e.g. Beech and Brown (2000), have reported optical intensity fluctuations in fireball observations and have suggested that these arise from rotational modulation of ablation processes. These fluctuations have shown up in the frequency range from a few to as high as 500 Hz.

Hawkes and Jones (1978) have made theoretical estimations of the rotation rates of small meteoroids, and obtained plausible frequencies of the order 50–13,000 Hz for 10^{-3} g meteoroids considering rotational bursting the only spin-limiting mechanism. Jones (1990) has since presented a mechanism of damping caused by absorption and re-emission of solar radiation. This kind of damping would lead to an equilibrium spin distribution for small interplanetary particles with a lower upper limit than Hawkes and Jones presented.

This report presents the first observations of pulsations in received power of faint radio-meteors, which could possibly be caused by spinning meteoroids.

2. Experiment overview

The 224 MHz EISCAT VHF radar located at a latitude of 69.58° N in Tromsø, Norway, was run with a dedicated meteor experiment for 6 h 02.00–08.00 UT (03.00–09.00 LT) on November 26, 2003. The time span of the experiment was chosen to admit the highest possible meteor rates and is too short to discern any diurnal variations. The beam was directed toward magnetic north with a 30° elevation providing a geometry as far from geomagnetic field-parallel as possible, approximately 17° from perpendicular. A sketch of the beam geometry is shown in Figure 1. The transmitted and received waves were left- and right-hand circular.

A 32-bit pseudo-random coded pulse sequence with a baud length of $2.4\ \mu\text{s}$ was used in the experiment, giving a total pulse length of $76.8\ \mu\text{s}$. The received signal was oversampled by a factor of four, which means a $0.6\ \mu\text{s}$ sampling period providing 90 m range resolution. The transmission/reception was alternated between two different frequency channels, 223.6 and 224.4 MHz, to lower the risk of range aliasing and to permit a high pulse repetition frequency. The channel-to-channel interpulse period was set to $2167\ \mu\text{s}$, enabling parameters such as meteor line-of-sight velocity and echo power to be monitored with a frequency of 461 Hz.

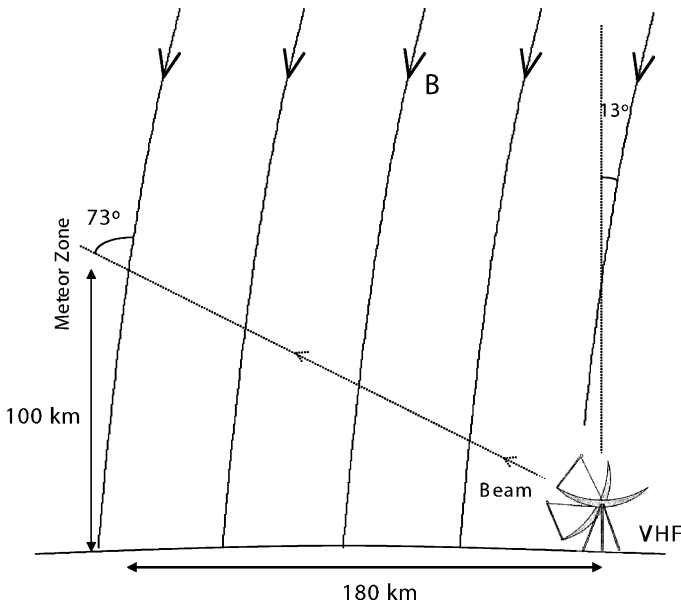


Figure 1. Sketch of the beam geometry of the experiment under consideration, 30° elevation and azimuth collocated with magnetic north.

The antenna of the EISCAT VHF radar is a parabolic cylinder. The beam is roughly elliptical and its cross-sectional power profile is Gaussian. The main lobe has a one-way half-power beam width of $1.2^\circ \times 1.7^\circ$. This is equivalent to 4×6 km at a range of 200 km, which corresponds to an altitude of 100 km with the given beam geometry.

The whole altitude interval illuminated by radio waves during reception reached from 86 to 123 km, chosen to include most of the EISCAT VHF meteor altitude distribution (Westman et al. 2004). The altitude interval illuminated by all 32 bits of the pulse sequence, in which full decoding is possible, was 92–117 km.

Previous EISCAT meteor experiments and results are described in a review by Pellinen–Wannberg (2004) and references therein.

3. Observations

About 2500 meteors were observed during the 6 h experiment. Many meteoroids have line-of-sight velocities lower than the minimum geocentric velocity of 11 km s^{-1} as they travel across the beam. No range-spread trail echoes have been found in the data set.

If a meteoroid passes through the radar beam at a large angle from the pointing direction, one can expect the received power of the meteor head echo to smoothly rise and disappear as the meteoroid traverses the Gaussian-shaped main lobe of the antenna in a time frame of the order of a tenth of a second. Approximately 10% of the detected meteors have a transient behavior of this kind. An example is shown in Figure 2. Remaining events do not have such smooth profiles, and are probably manifestations of non-uniform ionization and/or fragmentation during the meteors' observability within the beam.

As the EISCAT VHF radar is monostatic and does not have interferometric capabilities, it is not possible to deduce in an unambiguous way how far from the centre of the beam a specific meteoroid passed. The figures in this first report from the experiment show plots of SNR versus time of individual observations, leaving out radar cross-section and meteoroid mass estimations for the time being.

Approximately 13% of the detected events show intensity pulsations in the frequency range 20–200 Hz in their power-versus-time profiles. Figure 3 shows an example of a pulsating event with a fluctuation frequency increasing from about 25 to 200 Hz throughout its detectable duration of 0.16 s in the radar beam. The power of some events pulsates with more regular rates. One example shown in Figure 4 has an almost constant fluctuation frequency of 50 Hz. Very few events have decreasing pulsation

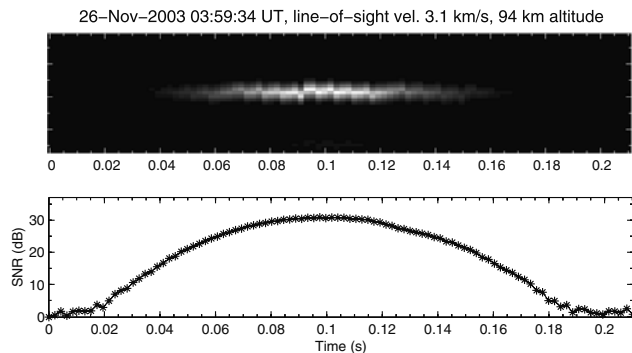


Figure 2. A meteoroid passing through the Gaussian-shaped antenna main lobe. The upper and lower panels show the meteor-aligned range-time intensity plot (upper) and the SNR (lower).

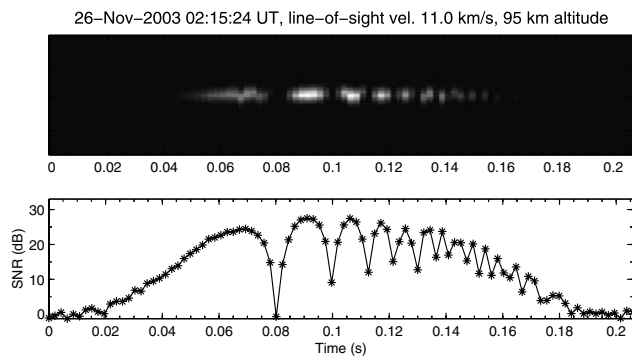


Figure 3. A pulsating event with a fluctuation frequency increasing from about 25 to 200 Hz throughout its duration of about 0.16 s. The upper and lower panels show the meteor-aligned range-time intensity plot (upper) and the SNR (lower).

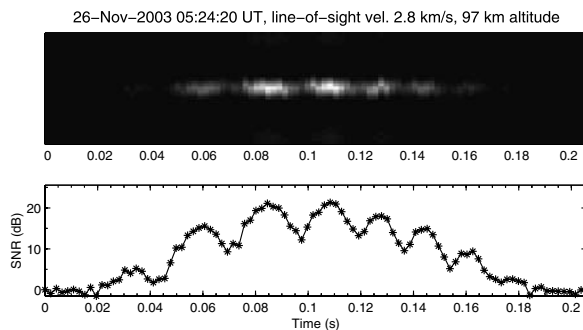


Figure 4. A pulsating event with a fluctuation frequency of about 50 Hz. The upper and lower panels show the meteor-aligned range-time intensity plot (upper) and the SNR (lower).

frequencies. The highest reconstructible power modulation of a detected signal in the experiment is 230 Hz.

Pulsating events have similar altitude distribution, line-of-sight velocity distribution and maximum SNR distribution as non-pulsating events. The received power fluctuates down to the noise floor for about 30% of the pulsating events.

4. Discussion

Recent investigations by Novikov et al. (2004) consider the influence of meteoroid rotation on the diffraction characteristics of underdense radio-meteors. They assumed $5 \cdot 10^{-4}$ g meteoroids rotating at 0–400 Hz. The investigations involved calculations of how much the electron volume density production inside a meteor trail would vary along the trail axis due to the varying cross-sectional area of a rotating cubic shaped meteoroid. In their results the electron volume density fluctuates with an amplitude of about 25% of the average density, but they conclude that the simulated fluctuations would be practically undetectable with meteor radars. The Fresnel diffraction patterns of echoes reflected from trails with fluctuating densities would be indistinguishable from patterns of echoes reflected from uniform meteor trails.

HPLA radars have a much higher sensitivity than meteor radars and can detect the small transient volume of dense ionization produced in the immediate vicinity of the meteoroid itself. Even a modest fluctuation of the ionization production should therefore be detectable provided its modulation frequency is suitable. For the EISCAT VHF experiment under consideration, the detectable frequency range is 10–230 Hz. The upper and lower limitations stem from the sampling frequency of 461 Hz and from the typical duration of an event, which is one tenth to a few tenths of a second.

The observed periodic power fluctuations cannot be explained by polarization fading or Faraday rotation as circular polarization was used. Multi-path fading due to, e.g. aurorae is not likely, especially as the geomagnetic conditions were very quiet during the campaign (deflections of the order of 10 nT).

The head echo target size is smaller than or equal to one atmospheric mean-free path (~ 0.1 m at 100 km) according to several different present scattering models (Close, 2004). The target is therefore much smaller than the radar wavelength ($\lambda = 1.34$ m) in the part of the measurement interval where most meteors are detected. The altitude distribution of pulsating events is not up-shifted compared to non-pulsating events. Thus, target-wavelength resonance effects are unlikely to be the cause of the pulsations.

5. Conclusions

The fluctuations of received power in echoes from the faint meteors observed with the EISCAT VHF radar are the first of their kind to be presented. Several authors have reported similar pulsations in optical observations of fireballs. The process causing the radar echo power pulsations has not yet been identified. Plasma effects are the most likely cause, a possible mechanism is for instance asymmetrical dust grains in rotation causing a modulation of the ionization rate. Future work includes analysis of tristatic UHF data and a more exhaustive investigation of possible mechanisms of the phenomenon.

Acknowledgements

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METEOROID BULK DENSITY DETERMINATION USING RADAR HEAD ECHO OBSERVATIONS

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Abstract. We present the results of a study of meteoroid bulk densities determined from meteor head echoes observed by radar. Meteor observations were made using the Advanced Research Projects Agency Long-Range Tracking And Instrumentation Radar (ALTAIR). ALTAIR is particularly well suited to the detection of meteor head echoes, being capable of detecting upwards of 1000 meteor head echoes per hour. Data were collected for 19 beam pointings and are comprised of approximately 70 min. of VHF observations. During these observations the ALTAIR beam was directed largely at the north apex sporadic source. Densities are calculated using the classical physical theory of meteors. Meteoroid masses are determined by applying a full wave scattering theory to the observed radar cross-section. Observed meteoroids are predominantly in the 10^{-10} to 10^{-6} kg mass range. We find that the vast majority of meteoroid densities are consistent with low density, highly porous objects as would be expected from cometary sources. The median calculated bulk density was found to be 900 kg/m^3 . The orbital distribution of this population of meteoroids was found to be highly inclined.

Keywords: meteoroids, bulk density, interplanetary dust, radar head echo

1. Introduction

Bulk density is a fundamental, though poorly constrained physical property of meteoroids. Techniques for determining meteoroid bulk density are quite varied and each is appropriate for a particular mass range of meteoroids. Methods ranging from the stratospheric collection of low mass interplanetary dust particles (Love et al., 1994) to observed light curves of higher mass photographic meteors (Rubio et al., 2002) have been used to determine meteoroid bulk density. The analysis we present combines the classical physical theory of meteors with radar head echo observations of meteors to determine meteoroid bulk density. Head echo observations have the advantage of providing precise position measurements for the meteoroid at each radar pulse return, from which velocity and deceleration may be determined (Close et al., 2001). Head echo observations are also unique in that when combined with an independent measure of mass, they allow observational

determination of bulk densities for meteoroids which are comparable in size to stratospherically collected IDPs. A new full wave scattering theory (Close et al., 2003) is used to provide an independent measure for mass from returned head-echo signal amplitude. Having these precise measurements together with an independent measure for mass permits accurate density determinations.

2. Data

Observations of meteor head echoes were made by the ARPA Long Range Tracking and Instrumentation Radar (ALTAIR). ALTAIR is a high power large aperture radar with interferometric capabilities which can operate simultaneously at VHF and UHF frequencies, 158 and 422 MHz, respectively. For reasons to be discussed, this analysis focuses primarily on VHF observations and the results presented apply to VHF data. The data in this analysis was collected during 19 observation periods each lasting 2 min on 8 August 1998, 17 November 1998, and 17 November 1999. These dates were chosen originally to detect meteors from the Perseid and Leonid showers. However, the very small limiting meteoroid mass detectable by ALTAIR resulted in all echoes collected being sporadic. This is due to the fact that the sporadic mass distribution index is much steeper than is the case for meteor showers (Ceplecha et al., 1998). As such these observations pertain mainly to meteors with radiants in the north apex sporadic source (Jones and Brown, 1993). The apex sporadic source of meteors has been shown to be the dominant sporadic source by other high power large aperture radars such as Arecibo (Sulzer, 2004), and Jicamarca (Chau and Woodman, 2004). It has been suggested that in general the apex sporadic source is the only source of meteors observable by high power large aperture radars (Janches and Chau, 2004). It is probable that this sensitivity of apex source meteoroids is a selection bias related to their high velocity.

There were 880 meteors detected during these observation periods. As a result of ALTAIR's high degree of calibration and interferometric capabilities, accurate three dimensional position data (within the beam) is available for each radar pulse return.

3. Analysis

Two criteria are applied to these data to reject anomalous points. The first criterion applies to the meteoroid position measurements. A linear least squares fit is made to the meteoroid three dimensional position data to determine a fitted meteor path. All data points at a distance greater than three times the standard deviation in distance from the fitted position are

discarded. The second criterion applies to accelerating meteors. Approximately 10% of head echoes detected by ALTAIR exhibit a slight acceleration at high altitude before showing normal deceleration (Close, 2004). This acceleration is interpreted as being unphysical and not reflecting the dynamic behaviour of the meteoroid, but is perhaps related to fragmentation or a plasma process as suggested by Close (2004). All data points associated with meteoroid acceleration are discarded.

Densities are determined via the drag equation from the classical physical theory of meteors (McKinley, 1961).

$$\frac{dV}{dt} = -\frac{\Gamma A}{m^{1/3} \rho_m^{2/3}} \rho_a V^2$$

where V represents velocity, Γ represents the drag coefficient, A represents the meteoroid shape factor, m represents the meteoroid mass, ρ_m represents meteoroid density and ρ_a represents the air density. When the following assumptions are applied to the drag equation, the resulting equation can be solved for bulk density. First, it is assumed that the drag coefficient Γ is 1, corresponding to complete momentum transfer between the meteoroid and air molecules. Second, following Bronshten (1983) the shape factor A is allowed to vary dynamically:

$$A = A_0 \left(\frac{m}{m_0} \right)^\mu$$

where m_0 is the initial mass of the meteoroid, m is the instantaneous mass, μ represents the parameter of shape variation and A_0 is the initial shape factor of the meteoroid.

$$\rho_m = \left(-A_0 \left(\frac{m}{m_0} \right)^\mu \frac{\rho_a}{\dot{V}} \right)^{3/2} m^{1/2} V^3 \quad (1)$$

Here A_0 is assumed to be 1.21, corresponding to a sphere, and $\dot{V}$ represents the instantaneous meteoroid deceleration. Equation (1) can be solved at each radar pulse return. The bulk density of a meteoroid is taken as the mean bulk density of all the radar pulse returns for that meteor.

Masses are determined by applying a new scattering theory (Close et al., 2003) to the observed radar cross section. Consequently masses have been determined with no assumptions about bulk density or deceleration. The Marshall Engineering Thermosphere (MET) (Owens and Vaughan, 2002) model is used for air density values. The parameter of shape variation μ , is

treated as a free mathematical parameter. The optimal μ is chosen such that the standard deviation in the bulk density calculated at each radar pulse return for a meteor is a minimum. This method is able to empirically account for fragmentation with the assumption that meteoroid bulk density should be constant with respect to time.

Orbits are calculated using the approach of Cepplecha (1987), with pre-atmospheric velocities determined using the theoretical correction developed by Baggaley et al. (1994) applied at the point of maximum electron line density along the observed head echo path.

4. Results and Discussion

As mentioned above this analysis presents only the result of the VHF observations. Observations made with VHF wavelengths can detect more of the meteoroid path than UHF wavelengths, as the apparent radar cross-section for meteor echoes scattering in the Rayleigh limit goes as λ^{-4} . Consequently VHF observations will observe more of the meteoroid's deceleration. With deceleration ($\dot{V}$) in the denominator of the bulk density equation (1), a smaller observed deceleration at UHF wavelengths will artificially shift bulk density higher.

From general considerations, we do not expect a priori that the bulk density for any of our observed meteoroids will exceed that of solid iron, i.e. more than 8000 kg/m^3 . Some calculated meteoroid bulk densities were found to be greater than this value. However, many of these un-physically high density meteoroids were also found to have very few data points and consequently very small observed decelerations. Thus we suspect strongly that these high density values are artifacts of the analysis procedure whereby only a small portion of the total trail is actually observed and often only very small decelerations are measured (i.e. if only the beginning of a trail is inside the beam). All meteoroids with a calculated bulk density greater than 8000 kg/m^3 have been excluded from the final analysis. The resulting data set contains 572 meteoroids.

The meteoroids in this analysis were primarily in the mass range of 10^{-6} to 10^{-10} kg with a mean mass value of $3.3 \times 10^{-8} \text{ kg}$ and a standard deviation of $1.6 \times 10^{-7} \text{ kg}$. These masses are approximately a factor of 100 more massive than meteoroid mass estimates for observations made with Arecibo (Janches et al., 2000; Mathews et al., 2001; Raizada et al., 2004). The majority of the observed meteors are not arriving directly down the ALTAIR beam. The mean angle of intersection between the meteoroid path and the ALTAIR beam is 40° . Throughout the observed meteoroid path, the mean percentage of meteoroid mass loss is 90%, indicating that the observed meteoroid paths represent a large portion of their true ablation meteoroid

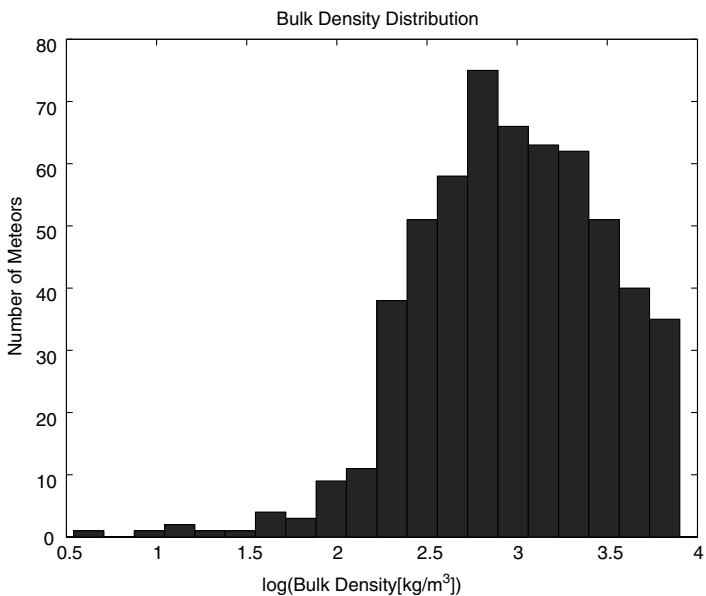


Figure 1. The bulk density distribution for 572 head echo detected meteoroids observed at VHF frequencies by ALTAIR.

path. The bulk density distribution is shown on a logarithmic scale in Figure 1. The median bulk density was found to be 900 kg/m³. The orbital distribution is shown in Figure 2. The mean orbital inclination of these

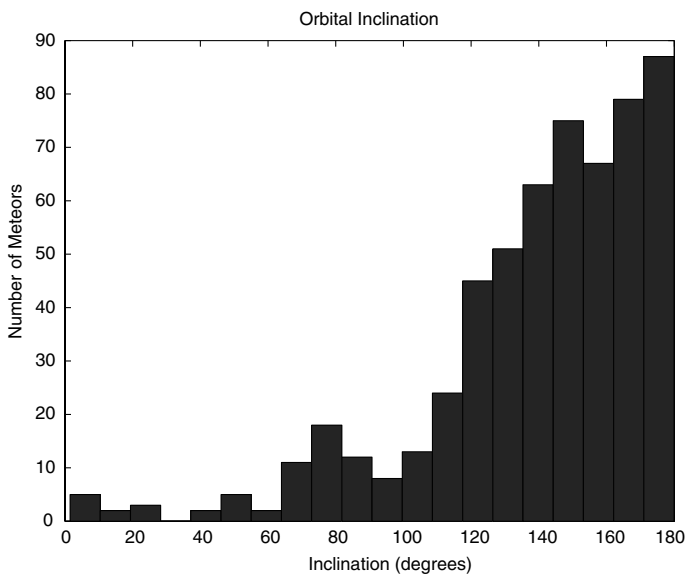


Figure 2. The orbital inclination of the same meteoroid population as shown in Figure 1.

meteoroids is 140° . This orbital distribution is consistent with orbital populations reported by Arecibo of apex source meteors (Janches et al., 2001).

The validity of the assumption of constant bulk density with respect to time used in our analysis needs further consideration. It has been suggested by Brownlee et al. (1983) that bulk density may be altered continuously during ablation as a result of thermal metamorphism on the meteoroid. Further investigation is required to determine what effect changing our assumption of constant bulk density would have on the bulk density distribution of this population of meteoroids.

Our results are consistent with Verniani (1973) where a median density of 800 kg/m^3 was found for 5759 faint radio meteors and with Rubio et al. (2002) where a mean bulk density of 810 kg/m^3 was found for 204 faint photographic sporadic meteors observed with Super-Schmidt cameras.

The bulk density of cometary nuclei have been determined through a variety of techniques. Through modeling the empirical perihelion advance, comet 19/P Borrelly has been found to have an estimated bulk density of $180\text{--}300 \text{ kg/m}^3$ (Davidsson and Gutiérrez, 2004). Through the modeling of the breakup of comet Shoemaker-Levy 9, treating the comet as a gravitationally bound agglomeration of spherical components, an overall comet density of 500 kg/m^3 was found (Solem, 1995). From estimates of mass determined from the variation in orbital period and volume from television photographs, comet Halley was found to have an average bulk density of 600 kg/m^3 (Sagdeev et al., 1987). It has long been generally accepted that many sporadic meteoroids are the products of the disintegration of cometary nuclei, dispersed to the point of no longer being associated with the orbit of the parent comet (Jacchia, 1963). In our case, the predominately retrograde orbits for meteoroids in our sample virtually assures that all particles are the debris products of long period comets. Our calculated median bulk density of 900 kg/m^3 is only slightly higher than the overall bulk density measured for several cometary nuclei. This suggests that it is possible that much of the porosity present in a cometary nuclei could be in the form of microporosity. However, the exact fraction of the porosity which might be in voids can only be constrained through modelling with estimates of the dust to ice ratio and the mineral grain density of the observed meteoroids. This is a question we hope to address in more detail from these data in the future.

5. Conclusions

ALTAIR head echo measurements of meteoroids in high inclination orbits with masses in the 10^{-6} to 10^{-10} kg mass range yield a median bulk density of 900 kg/m^3 . These results are consistent with cometary sources.

Acknowledgements

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RADAR MEASUREMENTS OF METEOROID DECELERATIONS

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Abstract. Measurements of meteoroid velocities and decelerations have been obtained from post- t_0 diffraction patterns present in echo signatures obtained from the multi-site AMOR radar operated at the University of Canterbury's research facility. The system allows the sampling of a meteoroid's velocity at separated points along the body's trajectory to yield decelerations. The technique has potential value in providing data on the relation between trajectory behaviour, drag characteristics, the physical structure of meteoroids and stream membership or orbit type.

Keywords: Deceleration, meteoroid, meteor-trajectory, radar

1. Introduction

For astronomical purposes a knowledge of the pre-atmospheric velocity components of a meteoroid is essential to accurately fix its heliocentric orbit. Although the process that produces the light and ionization for meteoroid detection via atmospheric interaction is the basis for its detection, this process inevitably imposes deceleration and complicates the determination of dynamical parameters. Knowledge of deceleration behaviour is valuable for an understanding of body drag and ablation mechanisms. Deceleration in the atmosphere (which is orders of magnitude greater than the acceleration due to gravity) is particularly significant for small particles – those sampled by sensitive transverse scattering geometry radar systems such as the AMOR system described here. The deceleration of a meteoroid depends upon its mass, speed, ablation conditions and trajectory orientation and single body model behaviour for the relevant particle mass regime implies values in the range approximately $2\text{--}20\text{ km s}^{-2}$. Direct measurements can be valuable in providing information on aerodynamical drag and hence physical characteristics.

Measurement of speed at two points along the trajectory can provide an estimate of the deceleration value. However this is complicated by the fact that deceleration (being proportional to atmospheric density) increases along the track. A more complete analysis requires measurements at several points along the trail so that for radar sampling a more complex system containing

more than the minimum employed three stations is necessary. A simplification often adopted in transverse geometry radar operation is to assume that the observed deceleration occurs at the point of maximum temperature and ablation rate and so close to the position of maximum ionization. Although inferred values of pre-atmospheric speed therefore cannot be precisely determined, first order effects can be accounted for. Radars employing radial geometry meteor plasma reflections are more readily able to sense velocity changes along the track (e.g., Hunt et al., 2004).

Here we report measurements using multi-site radar tracking of speeds at points separated along the trajectories of meteoroids and hence estimates of deceleration. Such have not appeared previously.

2. Technique

For the radar transverse reflection geometry mode, the time variation of the scattering cross-section of a meteoric plasma column can be described in terms of the generation of Fresnel intervals as the meteoroid progresses through the specular geometrical condition. The total scattered field and phase behaviour can be conveniently expressed in terms of the Fresnel Integrals C and S so that the amplitude of electric field, and therefore radar echo demodulated voltage $A(t)$, is proportional to

$$(C^2 + S^2)^{1/2}$$

and the scattered phase ϕ varies as

$$\tan(\phi) = \frac{-0.5 - S}{-0.5 - C}$$

(see for example McKinely, 1961; or more recently Baggaley, 2003). The functional form of A and ϕ for echo behaviour during the life-time of an echo for radar backscatter is shown in Figure 1. Where the time profiles assume that plasma train expansion due to diffusion is negligible.

A convenient analogue for the meteor echo is the optical case of diffraction at a straightedge. The complex diffraction function behaves in a way described very usefully by the Cornu spiral where the variable is the Fresnel parameter

$$x = \frac{2s}{(R_0\lambda)^{1/2}}$$

with s being the physical distance travelled by the meteoroid relative to the position of the specular point, R_0 is the specular point range and λ the radar wavelength.

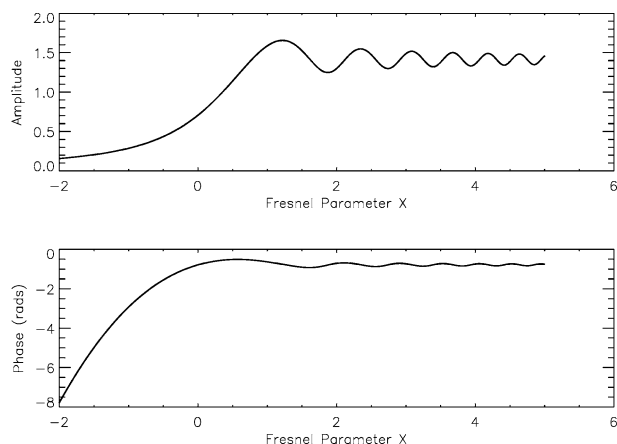


Figure 1. The real and imaginary parts of the ideal reflection behaviour for the case of no diffusion. Abscissa: Fresnel parameter (see text) proportional to time. Top panel: echo amplitude (arbitrary units). Bottom panel: phase (radians).

As the meteor approaches the geometrically orthogonal condition (t_0) a rapid increase of the signal power occurs as an increasing number of half period Fresnel intervals contribute. The phase increases monotonically reaching a maximum of close to $-\pi/6$ (actually 29.4°) at $x = 0.57$ (defining the phase as $-\pi/4$ when $x = 0$). The instant of maximum echo power occurs at $x = 1.217$.

The meteoric plasma column is free to move in the ambient atmosphere so that the local wind field will transport the plasma and introduce a phase gradient on the body echo. For any echo this phase effect can be recovered from the post t_0 phase behaviour to provide a measure of the atmospheric phase modification when analyzing each signal phase record to correctly recover the signature due to the meteoroid motion.

As the meteoroid traverses subsequent Fresnel intervals, the change in scattering cross-section after the echo maximum produces the diffraction pattern. It is this oscillatory signal that enables an estimate of the meteoroid speed: phase fluctuations can also be employed but with phase deviations of $< 20^\circ$ this method is not generally as useful in extracting speeds. Because of ambipolar diffusion, turbulence in the plasma train and meteoroid fragmentation, the plasma scatterer can be non-ideal with many meteoric ionization trains yielding distorted patterns so that the echo amplitude and phase behaviour do not provide useful signatures.

Because of diffusion a reliable measure is to take the first minimum in the amplitude: the first and subsequent minima and maxima occur for values of x which are as shown in Table I. For large values of oscillating cycles h , maxima and minima are given by $[(4h - 1)/2]^{0.5}$ with $h \geq 1$. If ΔT is defined as

TABLE I

Fresnel maxima and minima values of Figure 1. Excludes the first maximum at $x=1.21$

Maxima	2.344	3.082	3.674	4.183	4.637	5.049
Minima	1.873	2.740	3.391	3.937	4.416	4.848

the time between minima n and m then the estimate of speed for the time interval between those minima is

$$V = \frac{(R_0\lambda)^{1/2}(x_n - x_m)}{2\Delta T}$$

Setting $(R_0\lambda)^{1/2}/2$ equal to Z (the length of the first Fresnel zone) gives

$$V = \frac{Z(x_n - x_m)}{\Delta T}$$

A least-squares fit to the oscillatory pattern can achieve a speed accuracy of 1–5% depending on the echo signal-to-noise ratio and the number of diffraction cycles usable.

This technique has been used in several single-station radar surveys of meteoroid influx and velocity distributions subject to certain modifications (e.g., Šimek, 1969; Pecina, 1996). We note that the analysis modification of Pecina concerned speed accuracy resulting from the use of a wide range of possible values n and m cycles as above. Here the comparison is between separate Fresnel diffraction patterns employing the same n and m and from essentially the same source.

3. Application

The AMOR facility is a 26.2 MHz 60 kW 379 s⁻¹ pulsed radar designed to measure heliocentric orbits. The configuration of the system employs 8 km-spaced sites with remote site signal data transmitted via UHF frequency-modulated links to the control station (Baggaley et al., 1994; Baggaley et al., 2001). Three echo profiles are used to obtain time-of flight speeds: individual signals of echoes give amplitude-time profiles whose diffraction patterns can be analysed to give a scalar speed in the region of the specular reflection point for each echo.

For many meteors the creation of multiple reflection centres results from irregular ablation, irregular plasma density formation, rapid diffusion, and distortion of the ionization train due small-scale wind turbulence.

The resultant backscattered signals contain the summation of many different contributions towards both the the amplitude and phase to the extent that well-defined diffraction oscillations are suppressed. The fact that only a small fraction of echo events with an adequate signal to noise ratio yield usable patterns from which accurate post- t_0 speeds can be deduced will become apparent in this investigation.

We present results which comprise a sample (4851) of a large database of archived radar trajectories and orbits. This sample of non-stream meteors was obtained by the AMOR facility over the period January 1–4, 2004. The multi-site system has site separations of 8 km with the geometry of the site layout in relation to a detected meteor shown in Figure 2.

The radar signal reduction is achieved by software designed to sense the number of complete diffraction oscillation cycles (amplitude minima to minima). Determination of an accurate measurement of the change in speed for echoes received at the spaced sites requires those events to contain more than 5 complete cycles. This criterion is satisfied by 227 meteors (5.4%) of our database. Figure 3 shows two examples selected from those 227 echoes. Each meteor has produced a large number of post- t_0 echo diffraction pattern oscillations at all three echo receiving sites. Time of detection and trajectory information for these meteors is displayed in Table II.

In our sample, the proportion of events where all three echoes displayed many complete cycles were as follows: events with more than 7 cycles – 1.1%; events with more than 5 cycles – 3.4%; events with more than 3 cycles – 11.3%; events with more than 2 cycles – 15.0%.

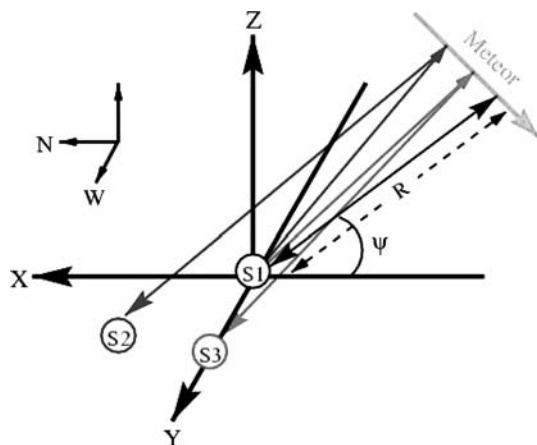


Figure 2. Schematic of the meteor detection geometry of the three site layout. Coordinate axes geographic north (N), west (W), local vertical (Z). Site S1 is the control (Home) site providing measurements of the echo elevation Ψ , range R and azimuth. S2 and S3 are located ~ 8 km from S1.

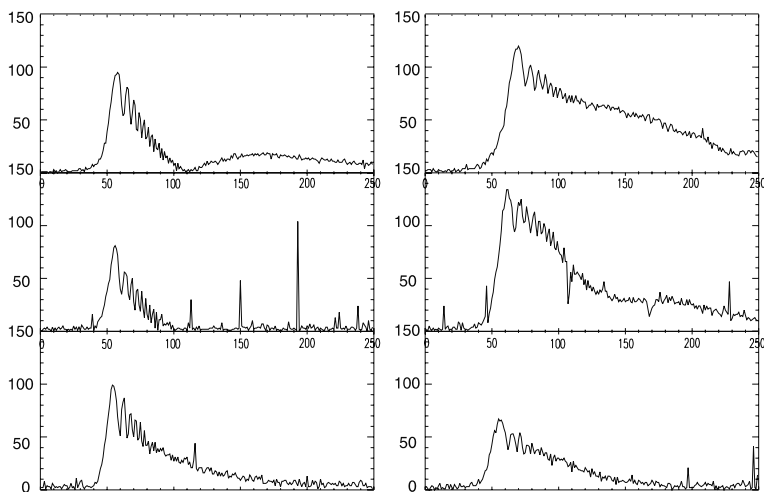


Figure 3. Echo amplitudes showing the diffraction patterns for two examples (left panels a, right panels b). Upper, mid, lower panels are, respectively the echo signals from the sites S1, S2 and S3. Ordinate is echo digitised signal voltage (0–256). Abscissa: radar pulses 0–250 (0.66 s).

TABLE II

Time of detection and trajectory information for the detected meteors of Figure 3 (Z–Trajectory Zenith Angle)

Time	Speed (km s^{-1})	Range (km)	Elevation	Altitude (km)	Z	Azimuth
(a) 02:12:21	38.2	170	33.4	95.1	33.7	351.7
(b) 02:39:06	27.1	136	40.1	88.5	41.4	17.4

4. Results

For the 227 examples of multiple phase cycles the decelerations are represented as a function of the meteoroid velocity as shown in Figure 4. For most individual echoes the uncertainties are rather large and average approximately 3 km s^{-2} . A few unrealistic positive deceleration values have uncertainties which are around 8 km s^{-2} . For large speeds there is some suggestion of two groups with mean decelerations of ~ 0 and 15 km s^{-2} . Figure 5 shows selected speed regimes. The small number of data limit the statistics but suggest mode values of 5 km s^{-2} with larger spread at larger velocities. However to separate the various factors responsible – zenith angle and ablation height – further studies are required and will be the subject of further work: here we draw attention to the technique and the potential for meteoroid dynamical analysis.

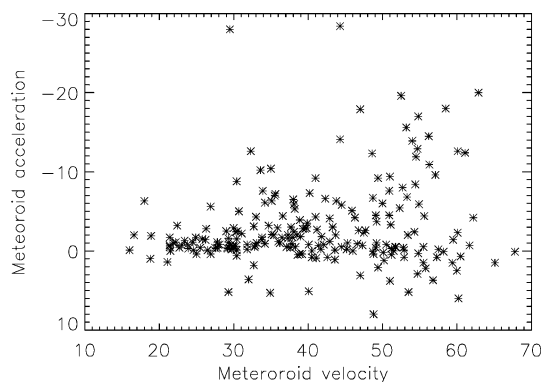


Figure 4. Deceleration (km s^{-2}) as a function of velocity (km s^{-1}) for the 227 echoes.

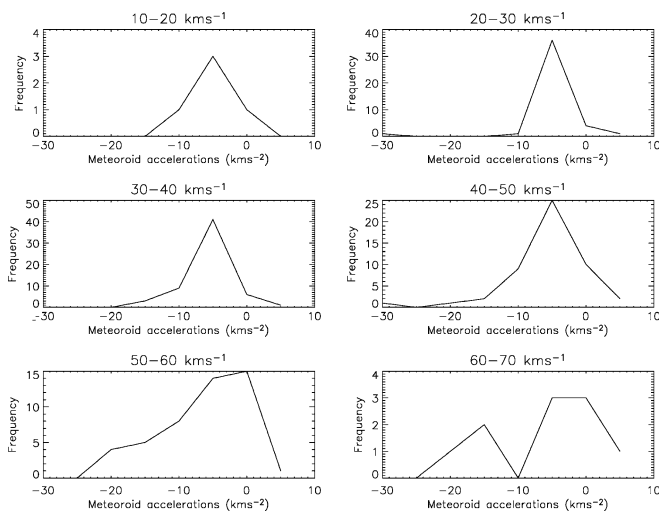


Figure 5. Deceleration (km s^{-2}) in velocity bins for the 227 echoes.

5. Conclusions and Discussion

The direct determination of the deceleration of meteoroid bodies is valuable both as necessary data to determine their pre-entry space trajectories and also the aerodynamics properties of ablation within the Earth's atmosphere. Examples have been presented of estimating deceleration achieved by sampling the velocity at separated points along the meteoroid trajectory. A limitation in the method is the small fraction of incident meteoroid that can be sampled (a result attributable to body fragmentation): only about 5% of all echoes are sufficiently rich in their diffraction cycles to provide sufficient speed accuracy.

With a knowledge of meteor trajectories and the heights at which radar reflections occur, the observed decelerations can be analysed to provide values, of the velocity-dependent ablation coefficient and meteoroid structure. The method has potential value in providing data on the relation between trajectory behaviour, the physical structure of meteoroids and stream membership or orbit type.

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RADAR MEASUREMENTS OF MACRO FRAGMENTATION IN METEORIODS

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Abstract. Fragmentation of an ablating meteoroid is a process that depends on the physical constitution of the body and the internal structure. These parameters are thought to control temperature gradients within the body. Phase signatures from the University of Canterbury's AMOR facility are shown to be able to resolve instances in which meteors are subject to gross macro-fragmentation where the meteoroid body disrupts into a few discrete components.

Keywords: Meteoroid, meteor, radar

1. Introduction

When a meteoroid is undergoing ablation in the atmosphere the forces binding the material of the body may be overcome to the extent that binding cohesion conditions are exceeded. Under these conditions, disruption of the original meteoroid occurs and multiple fragments may be produced. A meteoroid experiencing continual fragmentation can result in multiple small bodies each of which may contribute to the generation of light or ionization: here we use the term micro-fragmentation to describe this process. In contrast to studies which model fragmentation of larger bolide type objects, in this study we focus upon bodies which are typically a few tens of microns in size.

Much work has been based around the dustball model whereby a meteoroid with silicate-metallic or organic CHON type composition is represented as a conglomeration of grains held together by a low melting point glue. Rotation of the entering meteoroid is invoked to provide the mechanism for spreading the elementary grains laterally (see for example Fisher et al. 2000).

Additionally, continuous fragmentation is believed to occur during either or both the ablation process and the pre-ablation phase (Fisher et al. 2000, Campbell et al. 2000, and Campbell-Brown 2003). Such continual micro-fragmentation is the likely explanation for radar signatures from underdense

plasma meteors. It has long been recognized that many such echoes exhibit reflection coefficient versus time profiles clearly lacking in the expected diffraction oscillation characteristics of single body ablation – a result of overlapping time-displaced multiple ionization trails.

In contrast to the dustball model, optical records of bright objects provide evidence of fragmentation events where chondritic meteoroids fragment into a small number of discrete components (Brown et al. 1994, Hawkes 2004): here we adopt the term macro-fragmentation for this process. Radar records have also yielded multiple signatures in radial scattering measurements (Kramer 1968, Elford and Campbell 2001) but there is only sparse evidence of such a process in small radar-detected grains. In rare events, separation well outside the Earth's atmosphere have been reported (Hapgood and Rothwell 1981, Watanabe et al. 2003). Radar-observed macro-fragmentation events have been identified (Elford 2001a) reporting fragment separations of a few hundred metres during ablation: here we report fragment separations of several kilometres produced by a quite different process.

The phase records available from the AMOR radar system provide an ideal method of probing the fine structure signature of meteoric trains to provide evidence of disruption into a few discrete components – macro-fragmentation.

2. The Radar Method

The AMOR radar facility is a multi-station system operating at 26.2 MHz carrier frequency, 60 kW peak power and transmitting 379 pulses per second. It is designed to determine meteoroid trajectories in the atmosphere and uses, at the control site, a single narrow-radiation pattern transmitter together with a triple receiving antenna radio interferometer system supplying independent phases to fix the echo position. Time-of-flight velocity components available from the ~ 8 km spaced sites then provides the trajectory (Baggaley et al. 1994, 2001).

In this study the meteoroid trajectory and echo height are derived using the multi-station capability to enable estimates to be made of the breakup height of bodies undergoing macro-fragmentation.

3. Amplitude and Phase

AMOR signals can be separated into three amplitude components (obtained from both the control site and the two remote sites) and three phase components (obtained from the three control site interferometer antennas).

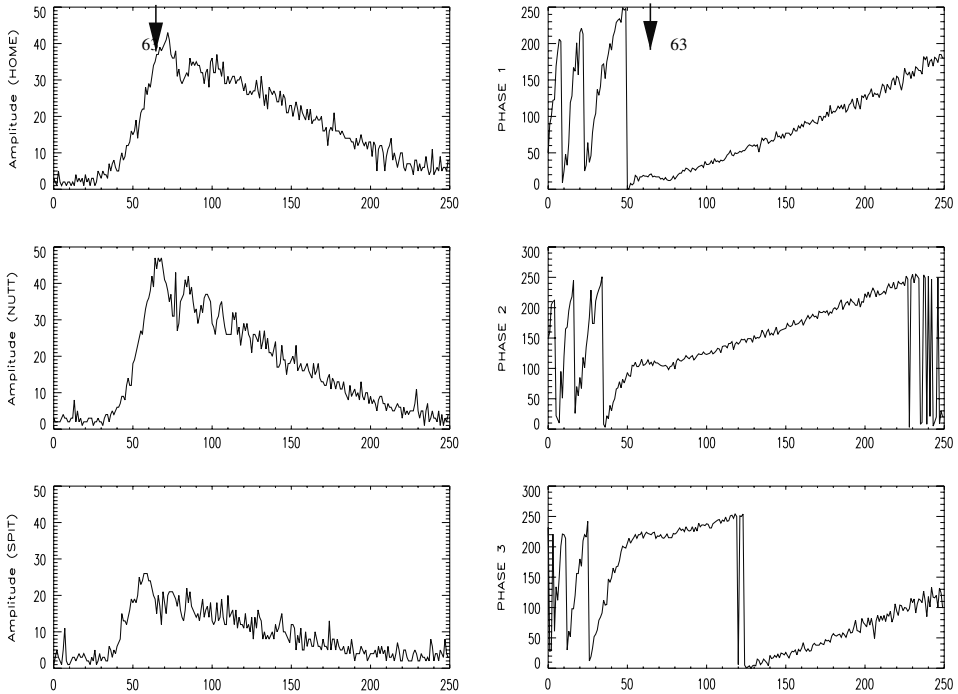


Figure 1. Example of three-site echo record: Left – control (locally termed Home) and remote (termed Nutt and Spit) site amplitude records. Right - control site unprocessed phase ($0-2\pi$ stored as $0-256$ from 8-bit digital format). Abscissa – radar pulses 1–250 (duration 0.66 s). The t_0 point occurs at index 63.

Figure 1 is an example of an underdense plasma echo showing the three control and remote site amplitude (left) and the three control site unprocessed phase records (right). Shown on the abscissa is time indicated by the radar pulse index with the total displayed time-span corresponding to ~ 0.66 s. The example shows the unprocessed signal: the radar can only sense the received signal phase within 2π and during data processing algorithms recover the true phase by backwards analysis of the records to remove 2π discontinuities and recover the monotonic phase-time function. The phase signal after such processing is applied is termed the unwrapped phase. The distance measured in units of Fresnel zone along the ionization track from the specular reflection point is termed the Fresnel parameter.

The theoretical Fresnel diffraction phase increases as the meteoroid approaches the specular reflection point to maximize at a Fresnel parameter value of $x = 0.572$. The term t_0 is used to describe the instant in time when the trajectory of the meteoroid is orthogonal to the radar line of site. In this example, the phase gradient, after index 75, corresponds to a radial drift of the plasma towards the radar.

The phase patterns produced during the echo arise from the creation of ionization along the meteoroid trajectory. Each provides a sensitive signature of the small-scale ionization distribution and can be analysed in terms of its rate of increase around the t_0 point and its post- t_0 behaviour to respectively determine the meteor speed and its radial drift in the wind affected atmospheric medium. In order to recover the signature of the phase generated due only to the moving meteoroid it is necessary to process the signal data to remove the phase gradient introduced by the ambient neutral wind after unwrapping the raw $0-2\pi$ phase record.

Each amplitude and phase component can be synthesized to form a complex record where the real and imaginary parts respectively describe echo power and phase. With the triple receiving antenna system (sensing direction) the records provide three independent complex variables which can be analysed using the Fresnel transform (FT) method (Elford 2001a) to determine the meteoroid speed.

The phase records of 4185 echoes (three day's data) were examined. A distinct feature was evident in 34 echoes (1.7%) where abrupt phase changes, additional to the main phase signature associated with a detected meteor, indicate the formation of an additional t_0 point. This corresponds to the phase signal obtained from an additional fragmented component of the meteoroid. Additionally, in the sample of echoes examined, there were 2 cases of three fragments. In all those cases showing a secondary feature the meteoroid component that arrived first had the larger speed. Figure 2 shows the amplitude and phase signals from such a macro-fragmenting meteor. The radar index corresponding to the t_0 point was determined by analysing the the phase behaviour transition from the rapidly changing phase gradient generated by the moving meteoroid to a constant small phase gradient arising from the plasma drift caused by the local wind field in the ambient atmosphere.

The respective speeds of the fragments were determined by the application of the pre- t_0 phase method on an isolated data windows selected to include the phase record prior to the t_0 points occurring at radar data indices 40 and 74 of the fragments. In this example the two distinct speeds were determined to be 67.3 and 71.3 km s⁻¹ with uncertainty ~ 0.2 km s⁻¹.

4. Disruption Height

From such distinct speed values and assuming earlier disruption of the body and model deceleration, an estimate can be made of the pre-ablation breakup height. Two dynamical mechanisms might be expected to contribute to a differential in speed of fragments recorded for the two echoes: ejection velocity differences at the fragmentation event and differential deceleration

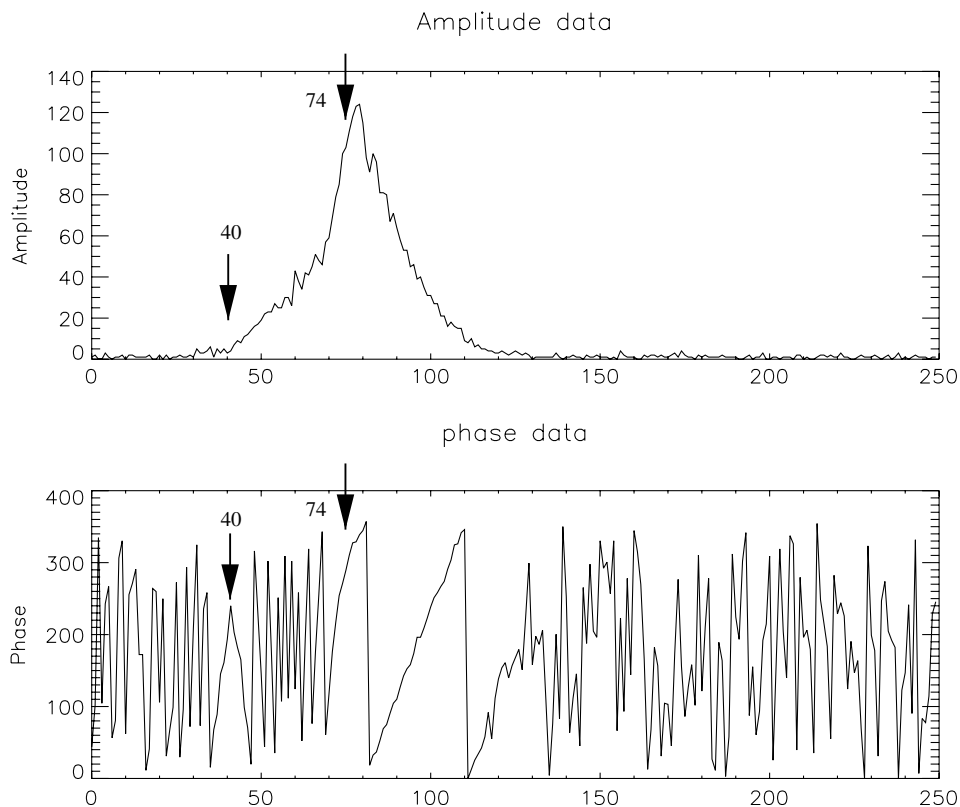


Figure 2. Fragmentation example: amplitude (top) and unprocessed phase (degrees) (bottom) components from one of the the control site antennas. Abscissa – radar pulses 1–250 (0.66 s). Indicated are the t_0 phase positions of the meteoroid fragments occurring at radar pulse indices 40 and 74.

due to e.g. different drag magnitudes due to different fragment dynamical cross-sections or body shapes. Two geometrical scenarios may be envisaged: longitudinal along-trajectory separation (so that speed differences produce coaxial fragment separation of radar-observed specular points) or divergence of the fragment trajectories after breakup (so that, because of the requirement for specular geometry, the radar reflection location points are spatially separated).

For a single body drag behaviour the velocity V and mass m at any height are related to those at pre-atmospheric entry, V_{inf} and m_{inf} by (see e.g. Baggaley et al. 1994)

$$V^2 = V_{\text{inf}}^2 - (2/\sigma)\log_e(m_{\text{inf}}/m) \quad (1)$$

with σ the ablation coefficient. At the maximum ionization deposition height this becomes

$$V^2 = V_{\text{inf}}^2 - 2.43/\sigma. \quad (2)$$

Using Bronshten's (1983) compilation of drag parameters, Baggaley et al. (1994) proposed a velocity dependence as $\sigma \propto V^{1.6}$ yielding (for a trajectory zenith angle Z of 45°)

$$V_{\text{inf}}^2 = V^2 + 0.81 V^{1.6}. \quad (3)$$

Statistically the echo point is expected to lie within about half a scale height of the ionization peak: a height change corresponding to 15% higher or 30% lower deceleration than given above. Deceleration is a function of (exponentially height-changing) atmospheric density and significant decelerations are confined to about one scale-height above the echo point so that the implied representative decelerations between a pre-ablation height of e.g. 150 km and echo heights of ~ 100 km are $\sim 3 \text{ km s}^{-2}$ at speeds of 60 km s^{-1} . Elford (2001b) using precise speed measurements reported similar values. We note that higher instantaneous values of deceleration will occur near the end of the ablation phase.

To demonstrate the potential of this type of phase record feature we estimate for the example illustrated using the longitudinal separation model. Let fragments be released coaxially with common initial velocity V_0 and decelerations a and $a + \Delta a$, then for constant deceleration and small event separation the difference in speeds after time t is approximately

$$\Delta V = t \Delta a \quad (4)$$

and the longitudinal separation

$$\Delta s = (1/2) a t^2. \quad (5)$$

With observed speeds V and $V + \Delta V$ occurring with time separation Δt ,

$$\Delta s = V \Delta t \quad (6)$$

so that

$$t = 2V(\Delta t / \Delta V). \quad (7)$$

These expressions assume constant deceleration and (4) applies to the two fragments at the same instant in time whereas in (6) and (7) ΔV refers to the fragments at the same position. The result therefore holds only for $\Delta t \ll t$. This backward processing can be improved by an iterative procedure to converge on a more accurate estimate: numerical examination shows that this simple approach yields an estimate that is a few percent too low. In the example given (Figure 2) Δt is 36 radar pulses equivalent to 0.095 s; speeds 67.3 and 71.3 km s^{-1} so that $t = 3.32 \text{ s}$, $\Delta a = 1.2 \text{ km s}^{-2}$ and pre-detection distance s is 246 km. Since, for single body drag dynamics for a given speed

trajectory angle and atmospheric density, the instantaneous deceleration is inversely proportional to particle radius, this differential deceleration is consistent with fragment sizes differing by 40%. The fragmentation height is $s \cos Z$ above the detection height. From the full trajectory velocity components provided by the multi-station geometry, radar height of 98 km and $Z = 32^\circ$ the fragmentation height is 306 km. We note that in this particular example the fragmenting body heliocentric orbit was hyperbolic.

5. Conclusions

This preliminary analysis indicates that fragmentation of meteoroids into predominantly two components occurs in about 2% of meteors, and the formation of three fragments in about 0.2%. The observed effect is highly unlikely to be due to the chance encounter within a fraction of a second of multiple distinct meteoroids along near identical tracks to produce the very stringent specular geometry conditions for detection. The AMOR system is able to provide the heliocentric orbits and the important question that can be addressed by this technique is whether fragmentation (as an indicator for example of body structure) is correlated with stream membership or (for non-stream meteoroids) with orbit type.

Acknowledgements

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RADAR CAMPAIGN TO DETERMINE THE DEPENDENCE OF INITIAL RADII OF METEOR PLASMA TRAINS ON TRAJECTORY AND ORBIT

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Abstract. Experimental and theoretical work on the transverse dimensions of meteoric plasma trains have not converged to provide generally accepted values: especially uncertain is the dependence of the train radii on meteor speeds. The roles of the meteoroid structure, fragmentation and plasma processes such as ion–electron instabilities need establishing. Knowledge of the quantitative spatial distribution of plasma in meteor trains is essential for a correct interpretation of fluxes and orbital characteristics. A current project is described which employs the AMOR 26 MHz radar facility in conjunction with a frequency managed radar operating at longer wavelengths designed to measure the ionization train radii, heights, atmospheric speeds and orbits of individual meteors.

Keywords: Meteor-train, plasma

1. Introduction

The excited meteoric species that generate radiation in the visible and associated ions and electrons are distributed in a roughly cylindrical shape of length ~ 10 km and time-dependent width of the order of metres. The mechanisms that lead to the dispersal of the excited neutrals include free and turbulent diffusion. Telescopic measurements (Hawkins and Whipple, 1958; Hawkes and Jones, 1978) and image intensified video (Pieres and Hawkes, 1993) are examples of width estimates of the visual trail. Trails have approximately Gaussian cross-section and a much used parameter is the half-width at $1/e$ of the Gaussian maximum, r_0 . While astronomical data on visually derived meteor magnitudes, masses and fluxes are not dependent on

r_0 (which is height and speed-dependent), for radar techniques similar astronomical parameters may be critically dependent on the plasma column width.

When modeling the reflection of radio waves from a meteoric ionization column, it can be assumed, in some circumstances, that the phase contributions from elements of the column are such that any radial expansion of the column is very small compared with the operating wavelength: in that case the phase addition is straightforward and the Fresnel integral method (e.g. Baggaley, 2003) is adequate. However if the radar operating wavelength is small or the echo reflection altitude large, then the transverse size of the plasma column might be comparable with the wavelength: for underdense plasma meteors (corresponding approximately to those fainter than equivalent visual magnitude +5) the train-penetrating radio-wave is scattered from electrons over a sensible depth resulting in phase differences for waves scattered in a cross-section. Ablated meteoric atoms suffer about 10 collisions before being reduced to thermal energies. However the measured r_0 dependence on height seems experimentally to vary less than simply according to inverse atmospheric density and the dependence of meteoroid speed is very uncertain. Radar measurements and theoretical treatments have been summarized in the compilations in Ceplecha et al. (1998) which suggest the form of r_0 as:

$$r_0 = \rho^a V^b$$

with a about -0.3 and b about $+0.6$ where ρ is atmospheric density and V meteoroid speed – but with considerable uncertainties in the exponent values. Indeed such a power law description may not adequately describe the important controlling agents. More recent experimental work is Campbell-Brown (2002) and Campbell-Brown and Jones (2003).

Thermal expansion of the plasma is only one of several processes contributing to the lateral spreading of a meteor train: the roles of meteoroid structure, continuous fragmentation and plasma instabilities need fixing. The body structure is known to depend on a meteoroid's source with e.g. asteroidal origin grains and different cometary streams having different densities and physical and chemical composition: the *effective* plasma column radius is the manifestation of several physical mechanisms. The presently described observational campaign fulfils the need to determine heights, speeds, atmospheric trajectories and orbits.

Knowledge of the plasma train radius is very important: in radars employing transverse geometry the reflection coefficient may be much reduced. This effect depends on height, speed and meteoroid origin so that any astronomical information may be degraded resulting in incorrect mass distribution indices, incorrect fluxes of particles and the inability to sense the

more porous low melting temperature organic-like grains ablating at high altitude. The height distributions obtained by Steel and Elford (1991) demonstrate well this effect – they suggest that 40% of the influx of grains is undetected. Although this (*height-ceiling*) effect is well known, experimental programs have generally failed to produce definitive values for the important parameters.

It is this inadequacy in our present understanding of the factors governing the transverse dimensions of meteoric plasma trains that prompts the present observing campaign to establish the roles of meteoroid structure, grain-type and solar system orbit and atmospheric trajectory. Here we describe a project using the 26.2 MHz AMOR radar that has the ability to measure for individual meteors – height (uncertainty <1 km), velocity (to $<1\%$) and heliocentric orbit used in combination with a low HF-band frequency-managed radar to sample simultaneously meteoric ionisation which will allow a better description of the plasma geometry to be obtained.

2. Radar Echo Frequency Characteristics

A robust method of measuring the overall plasma column width, r_0 makes use of the fact that the underdense meteoric plasma target width-dependent scattering cross-section is very wavelength-sensitive (for radar wavelengths $\lesssim 10$ m). If the transverse electron distribution retains a Gaussian density profile then the width-dependent target cross-section decreases (see e.g. McKinley, 1961) due to the finite plasma width by a factor

$$\exp\left(\frac{-8\pi^2 r_0^2}{\lambda^2}\right),$$

and the effective age of the train is $r_0^2/4D_a$ with D_a the ambipolar diffusion coefficient. If a radar system has identical radar equation parameters, then for underdense plasma conditions, the ratio of echo amplitudes due to the initial radius r_0 (m) effect using frequencies f_1 and f_2 (MHz) noting that $f = 300/\lambda$ for λ (m) follows as

$$\exp(4.4 \times 10^{-4} r_0^2 [f_1^2 - f_2^2]).$$

For two radars, one operating at 26.2 MHz and, for the lower radar a frequency between 5 and 10 MHz, the ratio changes by only $\sim 6\%$ over the lower frequency range. The purpose is to measure r_0 as a function of height, atmospheric speed V , and orbit. To secure incisive experimental data the two radar frequencies should be well separated.

There are additional factors that govern the characteristics of meteor echoes for two different radars:

- (a) For different operating frequencies the scattering cross-sections differ because of the different lengths of the Fresnel intervals: the echo amplitude due to this factor changes as $f^{3/2}$.
- (b) a further frequency-dependent effect is the finite velocity factor: in the time that the ablating meteoroid takes to travel through the central Fresnel interval the plasma train has expanded – so diminishing the scattering cross-section because the lateral spread may be comparable with a wavelength: for a given height small velocities will be attenuated compared to large velocities.
- (c) In the HF operating band the cosmic noise temperature T_c varies approximately with wavelength λ (m) as $T_c = 150\lambda^{2.3}$ producing differing signal/noise ratio.
- (d) While operation with well separated frequencies is necessary, achieving electrically similar transmitting and receiving antennas gains and patterns would also be ideal.

As discussed in Section 3, the operating frequency for the low frequency radar may be subject to interfering broadcast or unwanted echo signals so that a frequency flexible operation is required with the need for broadband antennas. Calibration in relative sensitivity of the two radars can be obtained by employing data for a particular class of echo: in the present project, echoes that are from meteoric trains having overdense conditions for both radars function as a baseline where the train transverse initial dimension does not affect echo amplitude.

3. Choice of Operating Frequencies

The AMOR facility operating at 26.2 MHz is the upper frequency radar employed for measuring speed, altitude and orbit. The lower frequency is dictated by the need for wide separation from the upper frequency sampling while at the same time ensuring freedom from radio station broadcast interference. Such ionospherically propagated signals can severely pollute the radio spectrum at low HF frequencies. A major governing factor in controlling the propagation of global broadcasting is the presence of irregularities in the ionospheric E-region: thin horizontally stratified layers of principally meteoric metal ions that undergo charge exchange reactions with O_2 and O . The factors that control these ionization irregularities are complex. A parameter that conveniently describes the ionization density in the layers is the sporadic-E blanketing plasma frequency, $f_b E_s$. These irregularities are also responsible for supporting ground backscatter from the operating radar. To ensure that ground-scatter by these layers does not occur and that no

support of broadcast propagation occurs for radar reception elevation angles greater than about 15° (the lowest angle for the horizontally polarized antenna used in the dual-frequency experiment) at ~ 10 MHz $f_b E_s$ needs to be < 2.5 MHz.

An ionosonde operated on a routine basis by the Canterbury University Meteor group located 20 km from our radar site provides data for the World Data Centre. The current and archived records of ionospheric parameters are available. Typical $f_b E_s$ values are shown in Table I. A full reference to the data indicates that operational success for the dual frequency campaign is statistically limited to post midnight for periods avoiding both local summer and times near solar cycle maxima.

Ionization underlying the meteor reflection height will act as a bi-refrangent medium for the propagation of transmitted plane polarized radio waves. Waves must twice traverse this lower E-ionospheric region. The geomagnetic field imposes two principal modes of propagation the manifestation of which is to cause rotation of the plane of polarization. For a given propagation path (determined by the meteor reflection point location) and ionospheric conditions, the rotation suffered varies inversely as the square of the operating frequency. For noontime conditions at frequencies less than 10 MHz multiple 2π rotations can occur: echo signals received using linear polarized antennas can be severely attenuated. Therefore periods of low E-region density are necessary.

Given these dictates, for radar operation below 10 MHz it is necessary to restrict to non-solar maxima nighttime in periods away from local summer. However such periods are only statistical and, to attain adequate echo data, some frequency flexibility of operation is necessary.

4. The Radars

For the 26.2 MHz (AMOR) radar, the narrow transmitting antenna beam provided by the 40λ long (0.5 km) narrow azimuthal pattern and multi-site narrow receiving antennas provide the required accuracy in elevation and azimuth for height, velocity and heliocentric orbit (Baggaley et al., 2001).

TABLE I
Typical ionospheric f_b, E_s parameters

Time	$f_b E_s$ Median value (MHz)	5% of time value exceeds
July 00–07	1.5	2.2
July 08–17	3.0	5.0
Jan 00–07	2.0	3.8
Jan 08–17	4.0	5.8

For this campaign the lower frequency radar operation requires a broadband antenna ideally of similar gain to the 26.2 MHz system. An antenna designed for this optimum operation is the horizontal rhombic. Such an antenna operates with near uniform gain over a factor of two in frequency. Such a non-resonant antenna was designed for the present purpose and employs a multi-wire rhombic antenna of leg-length 3λ , apex angle 50° and electrical height the same as for the higher frequency (0.3λ). The rhombic was designed to operate over a frequency band 5–10 MHz. It is necessary to have flexible operating frequencies for the transmitter and receivers so that spot frequencies can be changed as radio interference conditions dictated: frequency-management is necessary.

For the low frequency radar an ionosonde serves as ideal unit. The ionosonde (a swept frequency vertical ionospheric sounding radar) employed is a type IPS42: in ionosonde sounding mode, 40 μ s pulses at a series of frequencies on an approximately logarithmic scale are transmitted and the time delay to receipt of the echoes is recorded as a function of frequency. The rhombic was used as a common-mode antenna requiring a transmit receive (T/R) switch to isolate the receiver during high power pulse transmission. A T/R switch was designed to allow operation over the required $\sim 2:1$ range in frequency.

Besides its normal frequency scanning mode, the ionosonde can be set to operate on a single frequency. In this mode, the frequency can be set to any of the 576 frequencies using a set of 10 binary switches with an 11-th switch to change between the two modes of operation. The ratio of successive frequencies is 1.00543 ($1.00543^{128} = 2$). This is the mode of operation used for the current experiment.

A major modification was to provide the triggering of the transmitter and the T/R switch. In normal operation of the ionosonde, the pulses were obtained from the clock circuitry in the internal control electronics and were tied to the ionosonde's internal clock. For the current experiment, the pulses had to be derived from the (AMOR control) external source with provision for ionosonde lower (to limit the mean power output stage dissipation) prf (50 Hz) interlaced with the AMOR (400 Hz). In standard ionospheric sounding operation a logarithmic converter is used to record the data and set the echo reception threshold. For the present voltage-linear response a new linear demodulator was built to demodulate the output of the receiver. This consists of a high frequency op-amp with a diode in the feedback path. The high gain of the op-amp linearises the output. An operating mode was employed to provide interleaving the ionosonde transmissions with those from the 26.2 AMOR radar and multiplexing both data sets.

5. Summary

Detailed information on the transverse dimensions of meteoric plasma is essential to allow a correct interpretation of radar flux and orbit distributions. The transverse plasma train, at formation, may depend on plasma instabilities, meteor height and velocity, fragmentation process, meteoroid structure and type of orbit. Ionospheric effects have a critical impact upon radar design parameters and instrumentation. A detailed knowledge of these propagation effects is necessary to the success of the current dual frequency radar observing campaign.

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EXPERIMENTAL RADAR STUDIES OF ANISOTROPIC DIFFUSION OF HIGH ALTITUDE METEOR TRAILS

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Abstract. At altitudes above 93 km in the atmosphere, magnetic and electric fields can affect the modes and rates of non-turbulent diffusion of ionized meteor trails. Anisotropic diffusion is expected. Most theories of anisotropic diffusion, and indeed most experimental studies, have concentrated on the effects of the magnetic field in producing this anisotropy, and different rates of expansion are expected in directions parallel to and perpendicular to the magnetic field lines. In this study, we use interferometric meteor radars to investigate the dependence of the ambipolar diffusion coefficient on viewing direction relative to the magnetic field, and show that the dependence is at best weak when daily averages are used. We then demonstrate that the reason for this effect is that the positions of maximum and minimum diffusion rates varies as a function of time of day, and that daily averaging masks the anisotropy. One possibility to account for the observations is that this strong diurnal variation is a consequence of the electric fields in the upper atmosphere, which are often tidally driven. An alternative possibility is a diurnal cycle in mean meteor entrance speeds. We lean towards the first hypothesis, but both possibilities are discussed. We demonstrate our results with data from several sites, but particularly using the Clovar radar near London, Ontario, Canada.

Keywords: Anisotropy, diffusion, diurnal, electric field, ionosphere, magnetic field, meteors

1. Introduction

Meteors entering the Earth's atmosphere create trails of ionized plasma. The trails expand laterally by molecular diffusion processes at first, and possibly later by turbulent processes. Typical lifetimes are a few tenths of a second and less for so-called 'underdense meteors', and can be longer for overdense meteors. At low altitudes (below 90 km), the collision frequency is high, and collisions with neutral molecules damps the motions of the ions and electrons. However, at high enough altitudes, usually above 93 km, expansion can be anisotropic (e.g. see Cervera and Reid, 2000) with expansion being faster along the magnetic field lines. Theory relating to this effect has been presented by a variety of authors, including most recently Dryud et al. (2001, 2002), Oppenheim et al. (2000) and Robson (2001). However, experimental studies in support of these theories are rare. Most studies have covered only

short periods of time, and many have used only a few meteors in their investigations (e.g. Heritage et al., 1962; Zhou et al., 2001). In this work we will use a network of SKiYMET radars to study the diffusion processes experimentally, and then will use our observations to discuss the implications for current theories. Our results will include investigations using typically 50,000–100,000 meteors per observing site.

When radiowaves are scattered from a meteor trail, the amplitude of the radar signal received at the ground shows a rapid increase as the trail forms, then eventually decays in time. For the most common meteors, the so-called ‘underdense meteors’, the temporal variation in amplitude varies according to

$$A(t) = A_0 \exp\{-(16\pi^2 D_a t)/\lambda^2\} = A_0 \exp\{-\ln 2 t/\tau_{1/2}\}, \quad (1)$$

where t is time, λ is the radar wavelength, D_a is the ‘ambipolar diffusion coefficient’, and $\tau_{1/2}$ is the time for the amplitude to fall to one half of its maximum value. $A(t)$ is the received field strength at time t , with $t=0$ being the time at which the meteor signal reaches its peak amplitude, just prior to the onset of decay. Typical half-amplitude decay times $\tau_{1/2}$ for underdense meteors are of the order of 0.01–0.3 s for a radar operating at a frequency in the range 30–50 MHz. (e.g. see Hocking et al., 1997; Hocking, 1999, and references there in).

2. Instrumentation

All meteor radars used in this study are interferometric radars based around the design of the SKiYMET radar (Hocking et al., 2001a). This radar utilizes a transmitter antenna and five separate receiving antennas to locate meteors in the sky. Pulses of radio waves are transmitted at high pulse repetition frequencies (typically 1000–2500 Hz) and signals are received separately on the five receiving antennas. Each antenna then feeds signal directly into one of five receivers, and in-phase and quadrature components are digitized for each receiver. By comparing the phases of the received signals, meteor trail locations can be found to an accuracy of typical 1.5° (e.g. Jones et al., 1998). The radars used in this study were located at Resolute Bay (Nunavut, Canada, 75N, 95W), Yellowknife (NWT, Canada, 62.5N, 114.5W), London (Ont, Canada, 43N, 81W) and at Albuquerque, New Mexico (35.0N, 106.7W). The radar frequencies were 51.5, 35.65, 40.68 and 35.24 MHz, respectively. The Resolute Bay site is situated only a few hundred kilometers from the north magnetic pole. More details about the specific operation of the SKiYMET radars can be found in Hocking et al. (2001a, b).

3. Observational Method

Data have been accumulated from each of these radars over periods of many years. Generally data are available 24 h per day, all days of the year, except for occasional power outages and/or applications of the radars for non-meteor studies. For each meteor trail observed, a variety of parameters are recorded, including radial Doppler drift speed, amplitude, position in the sky (zenith, azimuth and range), and decay time. It is the decay time that is of most interest here. The procedure used to derive this has been described in Hocking et al. (2001a), but will be very quickly summarized here. The procedure involves, first, the identification of a meteor, which in itself is a very carefully designed algorithm. It involves detection of characteristics that distinguish it from E-region fading, lightning, overdense meteors, RF interference and other contaminants. Multiple simultaneous meteors in the same range gate are excluded, and background fading superimposed on top of any meteors is removed. Then the auto- and cross-correlation functions are determined between all possible pairs of receivers, and noise spikes at zero lag are removed. Check for consistency between radial velocities deduced using all combinations of antennas are performed, and finally the decay time is determined from the half-life of the autocorrelation function.

The first step in the analysis was to examine the zenithal dependence. Plots of the log of the inverse decay time as a function of height were obtained, and a least squares straight line was fitted, using data from (i) near overhead, (ii) at moderate angles from overhead (typically 25° – 45°) and then at large zenith angles (low elevations). While the random variability increased at low elevations, the least squares fitted line showed no noticeable variation in slope or mean offset. This has been shown in Hocking (2004), and we will not show it again. It is important simply because we need to remove the possibility that an apparent azimuthal anisotropy could be biased by zenithal effects if maxima in different azimuthal directions occurred at different zeniths. Henceforth our primary interest will be in the azimuthal dependence of the decay time.

Data were next selected from pre-specified height ranges, and then binned in zenith–azimuth cells, and the mean of the inverse decay was plotted as a function of azimuth and zenith. One thousand six hundred cells were used, and a 3×3 box-car two-dimensional running mean was also applied to the data to give some limited smoothing. Figure 1 is a representative example using data from the Clovar radar. In the case shown, we have separated out daytime and nighttime data, and have separated data above 93 km altitude from data below. We have chosen a transition height of 93 km because Cepelcha et al. (1998) and Elford and Elford (2001) generally agree on a height of about 93 km for the transition from isotropic to anisotropic diffusion. It is clear that below 93 km, there is very little azimuthal variation,

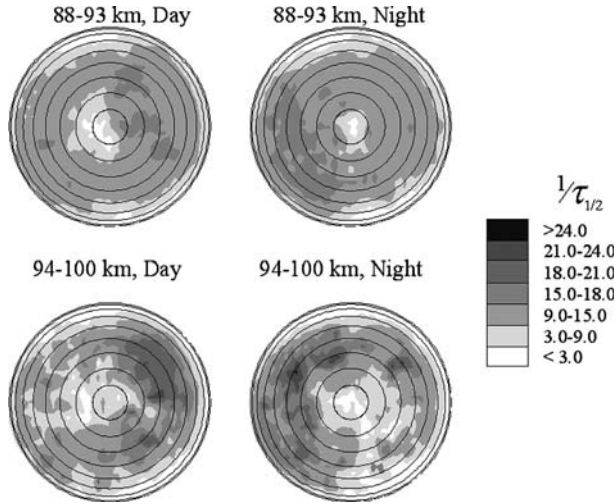


Figure 1. Contour map of the average inverse decay times as a function of zenith angle and azimuth for the Clovar radar, divided according to daytime and nighttime, for the period from June to August 1999. North is vertical, and the black circles show 10° steps in zenith angle. There are no areas with missing data except beyond 70° from zenith, where all meteors are ignored.

but above this height the grey-scale density changes quite substantially as a function of azimuth. In general, there are no bins with zero counts – the total number of meteors used exceeds 80,000. Except for the region immediately overhead (from which few meteors are detected), typical mean inverse decay time values $1/\tau_{1/2}$ in the height range 88–93 km are of the order of $9\text{--}15\text{ s}^{-1}$, but with occasional excursions to 15–18. The overall typical variation is less than 25%. However, in the height region above 93 km, there is much more structure, with mean values rising as high as 24 s^{-1} and falling as low as 9. This supports the notion that the anisotropy in diffusion rates is largest at greater heights.

4. Relevant Theory Pertaining to Geomagnetic Control of Diffusion

Above about 93 km, collision frequencies are small enough that electric and magnetic fields can cause anisotropic diffusion. The most recent theoretical studies of this effect are due to Dryud et al. (2001, 2002), Oppenheim et al. (2000) and Robson (2001). Other related references include Jones (1991), Cepelcha et al. (1998) and Elford and Elford (2001). Robson (2001), Equations (9) and (12), gives the following expressions for the diffusion coefficient for a meteor trail;

$$D_{\text{eff}} = D_{\text{parallel}} \cos^2 \alpha + D_{\text{perp}} \sin^2 \alpha,$$

where α is simply the angle between the viewing direction (which is perpendicular to the meteor trail) and the magnetic field lines, and where

$$D_{\text{parallel}} = D_{\text{perp}}(1 + \zeta) \quad (3)$$

with ζ being equal to $e^2 B^2 / (m_e \mu_i \nu_e \nu_i)$. Here, m_e is the electron mass, μ_i is the reduced mass of the neutral-ion pair involved in the collisions during diffusion, ν_e is the electron collision frequency and ν_i is the ion collision frequency with the neutrals. The diffusion is considered to be 'parallel' when $\alpha = 0$. Collision cross-sections (which relate to the diffusion coefficients) have been deduced using experimental laboratory data (e.g. Elford and Elford, 2001). At 95–96 km altitude, $D_{\text{parallel}}/D_{\text{perp}}$ is of the order of 10, while at about 93 km, $D_{\text{parallel}}/D_{\text{perp}}$ is of the order of 2. At lower heights, this ratio quickly approaches unity. Hence anisotropy effects might be expected to be important above typically 93 km, according to this theory. As a result, we would expect to see different meteor-trail radar lifetimes depending on the angle at which the trail is seen by the radar relative to the magnetic field. Lesser (or no) effect should be evident at heights below this altitude.

5. Results

Figure 1 showed inverse decay times for heights from 88 to 93 km and above 93 km. Henceforth we will concentrate solely on meteors at heights above 93 km. We have produced similar plots to those of Figure 1 at several sites, including for radars at Resolute Bay, Yellowknife, London (Ont.) and Socorro (NM). Using all-day averages, no consistent pattern of maxima and minima was apparent with regard to angle relative to the magnetic field lines. The Clovar radar (London, Ont., Canada) showed a broad maximum at about 60° east of magnetic north for typical summer conditions, with a secondary maximum 30° west of magnetic north. The radar at Albuquerque showed a broad maximum to the north in summer, and the radar at Yellowknife showed maxima to the geographic east and west. Furthermore, it can be seen from Figure 1 that the region of general maximum values of $1/\tau_{1/2}$ is different during night and day. This is not consistent with previously published theories. All of these observations suggest that the diffusion anisotropy also depends on additional factors other than the magnetic field strength and orientation.

The above results suggest both latitudinal and temporal variability of the position of the maxima. We will concentrate here on temporal variability. In order to investigate the temporal variability, the data were grouped into 3-h

clusters, according to time of day, and plotted as in Figure 1, for the data above 93 km. The results for the Clovar radar (summer, 1999) are shown in Figure 2. Over 80,000 meteors were used to make these plots. We have shown four times of day: 0000–0259, 0600–0859, 1200–1459, and 1800–2059. The position of the maximum rotates clockwise with increasing time. The times 0300–0559, 0900–1159, 1500–1759 and 2100–2359 were also consistent with this trend, but have not been shown in order to save space.

In order to quantify this directionality, a vector has been calculated with the components [$\langle 1/\tau_{1/2} \cos \phi \rangle$, $\langle 1/\tau_{1/2} \sin \phi \rangle$], where ϕ is the azimuthal angle of each meteor location, $\tau_{1/2}$ is the decay time and $\langle \rangle$ refers to an ensemble average. Such an average produces a vector which points in the general direction of the larger values of $1/\tau_{1/2}$, or direction of fastest diffusion. These vectors are shown at the centre of each diagram in Figure 2. When the vectors for all 8×3 -h time bins were plotted on the same graph, Figure 3 resulted. This result is for the Clovar radar, but similar results existed at other sites. The position of maximum diffusion clearly changes with time along a quasi-elliptical path. An ellipse has been fitted to the points. The ellipse is rotated 18° north of east, while magnetic north is 8° west of north at London, Ont., Canada. An obvious diurnal variation exists. One possible reason is that there is tidal influence, probably via an $\mathbf{E} \times \mathbf{B}$ effect. It is well known that there are large electric fields in the upper atmosphere, driven in part by tidally induced winds, and we propose that the elliptical motions seen here could be a manifestation of these tides. In summer over London,

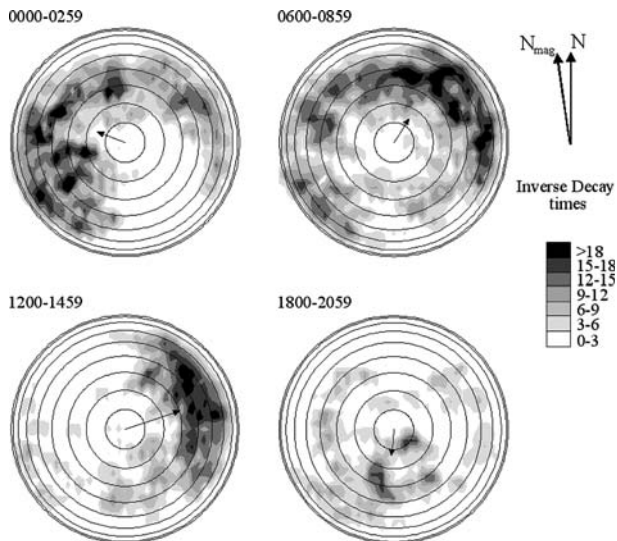


Figure 2. Average inverse decay vectors plotted as a function of time of day for the Summer of 1999 with the Clovar radar. Times are local time (= UT-5 h). Circles show 10° steps.

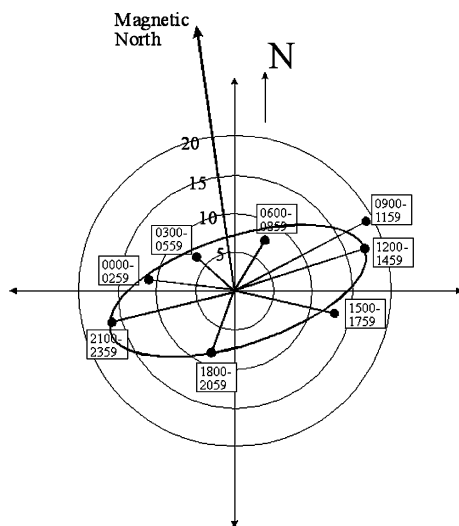


Figure 3. Inverse decay time vectors plotted as a function of local time of day (UT-5 h). An ellipse is fitted to the tips of the vectors.

Ontario, the neutral wind tides are a mixture of diurnal and semidiurnal components, and at the upper altitudes (near 100 km) the diurnal tide tends to dominate, though a semidiurnal component certainly exists (Thayaparan et al., 1995). We do not know at this time how the relative strengths of the diurnal and semidiurnal electric fields are distributed, though we expect similar distributions to the wind field. However, if indeed electric fields are affecting the observations, then the current theoretical analyses need to be considerably improved, since the hypothesis that the diffusion coefficient anisotropy is a simple function of the magnetic field is inadequate. We suggest that future theoretical analyses need to include externally imposed electric fields in order to produce accurate simulations of diffusion rates in the upper atmosphere.

An alternative proposal has been suggested by J. Baggaley (private communication). The average atmospheric impact speed of meteors exhibits a strong diurnal variation. At approx. 0600 LT the Earth's Apex is highest, the associated radar-detected meteors have azimuths centered on north looking (for the Clovar radar), and speeds are largest. Therefore heights increase so that diffusion coefficient increase and diffusion times decrease, increasing the value of $1/\tau$. The rotation and times in the author's ellipse are in the expected direction. However, the difficulty with this explanation is that it is unclear why the effect would be more dominant at the greater altitudes, and why no reciprocal effect is seen below 88 km (Figure 1). Nevertheless, at this stage our primary goal is to report the results – clearly discussion about the causes may involve substantial future work.

6. Conclusions

Studies of meteor diffusion rates at several meteor radar sites, using large numbers of meteors, show that there is an anisotropy in the rate of expansion of the trail for trails formed above 93 km altitude. However, the anisotropy is not a simple function of the strength and orientation of the magnetic field, but shows a distinct diurnal variation. We have demonstrated this with the Clovar radar near London, Ont., Canada, and have also seen this effect at other radars ranging in location from the north magnetic pole to a latitude of 35N (Albuquerque, NM). We suggest that this diurnal variation is due to external electric fields which are tidally driven, and propose that future modeling of meteor trail diffusion for altitudes above 93 km should also consider such fields.

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RADAR OBSERVATIONS OF TAURID COMPLEX METEOR SHOWERS IN 2003: ACTIVITY AND MASS DISTRIBUTION

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Abstract. Results of Ondřejov radar observation of Taurid complex meteor showers, i.e. ζ Perseids, β Taurids, S and N Taurids, performed in 2003, are presented. We have found some mass segregation within ζ Perseid, β Taurid and S Taurid showers. We have also established conspicuous lack of long duration echoes (with $T \geq 3$ s resp. $T \geq 5$ s) in S and N Taurid showers. The lack within remaining showers is not so pronounced but still persists.

Keywords: Activity, mass distribution, meteor showers, Taurid complex

1. Introduction

The Taurid meteor complex with its exceptional features offers a unique opportunity for the study of the evolution and origin of meteoroid streams in general, and of the problem of cometary/asteroidal origin of meteoroids in particular. Comet Encke is known to be a parent body of ζ Perseid, β Taurid, Northern (N) and Southern (S) Taurid showers (Whipple and Hamid, 1952). These four showers constitute the Taurid meteor complex. The former two showers are typical day-time showers while the latter ones are active during night time. The N and S Taurids are due to their lower rates better known from photographic than from visual observations. Cook (1973) noticed that these streams cannot be resolved from one another visually. As for their radar studies only a few have been performed.

The activity of meteor stream can be studied from various aspects. We will confine ourselves here to the activity profiles and mass distribution of radar echoes within these showers and the mass segregation between inner and outer parts of particular shower (i.e. the activity of meteors of different masses as a function of solar longitude).

This article presents results of observation of the showers in question performed in Ondřejov in 2003.

2. Observations

The Ondřejov meteor radar operates at 37.5 MHz, with peak power of 10 kW and pulse repetition frequency of 500 Hz. All other details concerning its construction and operation can be found elsewhere (Plavcová and Šimek, 1960). The way of observations in 2003 was the same as we have used during Leonid campaign (e.g. Pecina and Pecinová, 2004) regarding the different radiant.

The time intervals of observation of particular shower in hours as well as days of observations divided into background and shower periods are collected in Table I.

The relevant time interval of observations of day-time showers had to be cut to values listed in Table I due to a strong outer interference lasting for about 4 h appearing after 8 UT in 2003. The corresponding time of perception of N Taurids was shorter to have a time span for subsequent observations of Leonid shower. The difference of time intervals in shower and background periods of S Taurids and N Taurids is due to different radiant position in that periods. The rates plotted in Figures 1 and 2 are assigned to intervals listed in Table I.

3. Activity

The activity of the Taurid complex showers is represented by the activity of meteors divided into 4 duration groups as it is usual in meteor radar studies. The first group comprises underdense meteors, i.e. meteor echoes with duration $T < 0.4$ s, the remaining groups contain overdense echoes, from which the first one is the group of echoes with $T \geq 0.4$ s, the second group

TABLE I
Days and hours of observation of Taurid complex showers in 2003

Shower	Periods of observation	
	shower period	background period
ζ Perseids	June 6–12	May 30–31
	4–8 UT	4–8 UT
β Taurids	June 25–30, July 1	June 19, July 7–8
	5–8 UT	5–8 UT
S Taurids	November 1/2–5/6	November 28/29–29/30
	19–5 UT	17–3 UT
N Taurids	November 11–14	December 3
	18–23:50 UT	16–23 UT

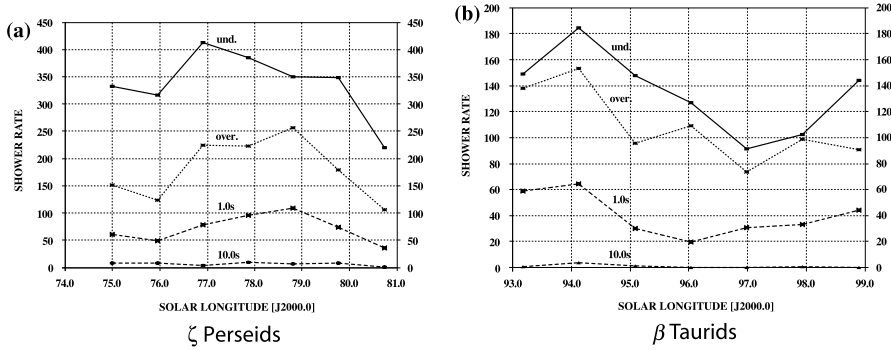


Figure 1. Activity of the ζ Perseid and β Taurid meteor showers in 2003 as a function of solar longitude, $L_{\odot}$ [J2000.0]. The full curve represents underdense meteor echoes (marked as und), the remaining 3 curves represent overdense echoes. The curve describing all overdense echoes is marked as over, the other two correspond to echoes with respective duration $T \geq 1$ s and $T \geq 10$ s.

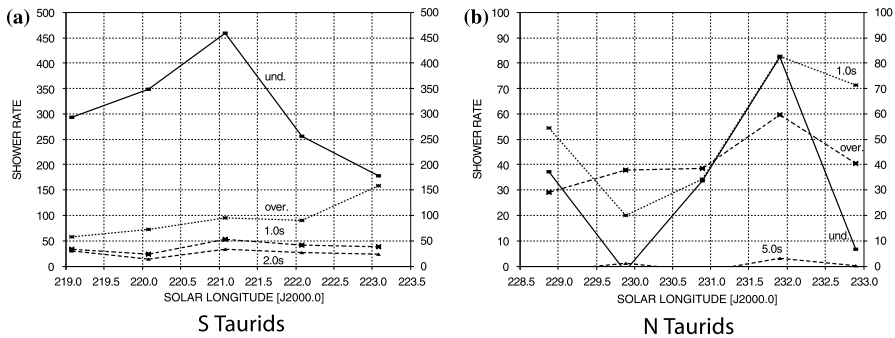


Figure 2. The same as in Figure 1 but for S Taurid and N Taurid showers. However, the last overdense group comprises echoes with $T \geq 2$ s and $T \geq 5$ s, respectively.

with $T \geq 1$ s and the third one with $T \geq 10$ s. The corresponding masses are given in the next section in Table II. The rates in all figures are rates of shower echoes obtained by subtracting sporadic background echo rates from echo counts observed within corresponding hours. The points in graphs represent middle of the relevant intervals. We will compare the positions of activity peaks with data given by Cook (1973). His solar longitudes are further on referenced to equinox of J2000.0.

3.1. ζ PERSEIDS

The ζ Perseids were observed by the same radar also in 1967, but the results were never published. We use these data here for comparison with our

TABLE II
Mass of a meteoroid having duration T in particular time instant, expressed in grams

Time [UT]	z_R	$T=0.4$ s	$T=1$ s	$T=2$ s	$T=5$ s	$T=10$ s
ζ Perseids						
3	82°	0.10	0.27	0.58	1.57	3.34
4	72°	0.04	0.12	0.25	0.68	1.44
5	63°	0.03	0.07	0.16	0.43	0.92
6	53°	0.02	0.05	0.12	0.32	0.68
7	44°	0.02	0.05	0.10	0.26	0.56
β Taurids						
4	79°	0.07	0.19	0.41	1.11	2.37
5	70°	0.04	0.10	0.22	0.59	1.25
6	60°	0.03	0.07	0.14	0.39	0.83
7	51°	0.02	0.05	0.30	0.30	0.64
S Taurids						
19	66°	0.031	0.084	0.179	0.487	
20	56°	0.022	0.060	0.127	0.344	
21	48°	0.018	0.049	0.104	0.283	
22	41°	0.016	0.043	0.091	0.248	
23	37°	0.015	0.040	0.086	0.233	
0	38°	0.015	0.041	0.087	0.237	
1	42°	0.016	0.044	0.093	0.252	
2	48°	0.018	0.050	0.104	0.283	
3	57°	0.026	0.061	0.130	0.354	
4	66°	0.031	0.084	0.179	0.487	
5	75°	0.051	0.138	0.293	0.797	
N Taurids						
18	67°	0.032	0.088	0.187	0.509	
19	58°	0.023	0.063	0.134	0.365	
20	48°	0.018	0.049	0.104	0.283	
21	39°	0.015	0.042	0.086	0.240	
22	32°	0.014	0.038	0.081	0.219	
23	27°	0.013	0.036	0.076	0.207	

present result in order to show possible long-time difference between the observations from 1967 and 2003. The results of 2003 observation is delineated in Figure 1a.

There is a clear difference between the appearance of the underdense and overdense meteor echoes. The activity of underdense echoes culminated about 2 days earlier than that of overdense. It indicates the mass segregation between the inner and outer part of the shower. Further, we can see negligible activity of echoes with $T \geq 10$ s indicating that the activity of overdense

echoes was only due to the ones having durations shorter than 10 s. All previous categories showed maxima within 6–7 UT. This corresponds to $L_{\odot} \simeq 76^{\circ}81$ in case of underdense echoes (June 8) and $L_{\odot} \simeq 78^{\circ}81$ (June 10) for overdense echoes. In 1967 observation, the activity of all categories of echoes peaked at 9–10 UT June 7 corresponding to $L_{\odot} \simeq 76^{\circ}42$, which is close to $L_{\odot} \simeq 76^{\circ}70$ given by Cook (1973). No mass segregation between the inner and outer parts of the shower was detected in 1967. Also in this observation only meteors producing echoes with duration shorter than 10 s were recorded. The observed difference between results from 1967 to 2003 seems to indicate possible long time variability of shower activity. However, to confirm this finding, further observations are required.

3.2. β TAURIDS

It is evident from Figure 1b. that this shower shows similar behaviour in all duration groups with a peak at $L_{\odot} \simeq 94^{\circ}13$ corresponding to 6–7 UT June 26. There is probably only a slight mass segregation within this shower, notice the different behaviour of all overdense echoes as compared with the echoes of duration $T \geq 1$ s around $L_{\odot} \simeq 96^{\circ}$. It probably implies different behaviour of echoes of duration $0.4 \text{ s} \leq T \leq 1 \text{ s}$ in comparison with remaining population. We have observed only echoes with $T \leq 10$ s. Cook (1973) gives the peak at $L_{\odot} \simeq 96^{\circ}70$ (June 29).

3.3. S TAURIDS

We have found different behaviour of underdense and one category of overdense meteors, see Figure 2a. The underdense echoes have peaked at $L_{\odot} \simeq 221^{\circ}10$ on Nov. 3 which is observed also for overdense echoes with $1 \text{ s} \leq T \leq 3 \text{ s}$ but not for $0.4 \text{ s} \leq T < 1 \text{ s}$. This last group maximum was at $L_{\odot} \simeq 223^{\circ}08$. Only echoes with $T \leq 3 \text{ s}$ were observed. Comparing this fact with the limiting duration found in previous showers there is evident a more severe depletion of this shower from larger meteoroids since all the showers have very similar velocities. The shower peak activity of underdense echoes is consistent with the Cook's value $L_{\odot} \simeq 220^{\circ}70$, however, the overdense echo curve for echoes $0.4 \text{ s} \leq T \leq 1 \text{ s}$ is shifted by over two degrees. There is also evident mass segregation within this stream.

3.4. N TAURIDS

The N Taurids (Figure 2b) exhibit a similar activity trend for all categories of echoes with one common peak located at $L_{\odot} \simeq 231^{\circ}90$ corresponding to

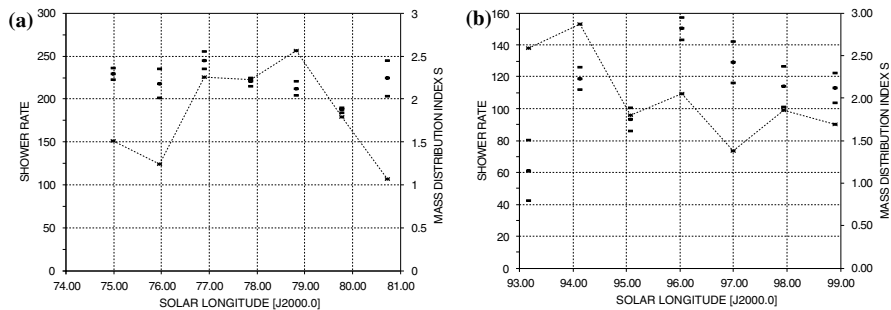
Nov. 14. We have not found any mass segregation within this shower. Again in contrast is the value of the peak position given by Cook for $L_{\odot} \simeq 230^{\circ}70$ (Nov. 13).

4. Mass distribution

The mass distribution index, s (see, e. g. McKinley, 1961), has been computed from the $\log N$ vs. $\log T$ fit using the Kaiser's formula Kaiser (1955)

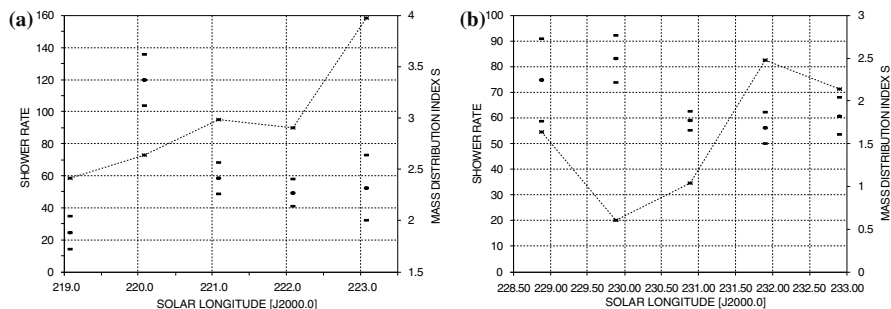
$$\log N = -(3/4)(s - 1) \log T + \text{const}, \quad (1)$$

where N is the cumulative number of echoes having duration greater than T . The courses of s -index together with activity profiles are depicted in Figures 3 and 4.



a. ζ Persids – mass distribution index s b. β Taurids – mass distribution index s

Figure 3. Comparison of the courses of the mass distribution index s represented by squares (with error bars) and shower activity of the overdense echoes represented by dotted curves, as a function of the solar longitude, $L_{\odot}$ [J2000.0].



a. S Taurids – mass distribution index s b. N Taurids – mass distribution index s

Figure 4. The same as in Figure 3. but for S Taurid and N Taurid showers.

They can be characterized by their lower value around the peak of activity of overdense meteors sometimes having minimum 1 day after activity peak. The mass corresponding to particular duration T at chosen time instant of observation can be inferred from Table II. These masses have been computed in the same way as in Pecina and Pecinová (2004) with the only exception of diffusion coefficient (taken for height of 90 km, see e.g. (McKinley, 1961)) and velocity $v_{\infty} = 30 \text{ km s}^{-1}$. The first value of s for β Taurid shower is rather exceptional. We tried to compute it using also other method than the Kaiser's one and we have obtained $s = 2.53 \pm 0.55$ (see Pecina and Pecinová, 2005).

5. Conclusion

We can draw in the light of previous sections the following conclusions. The positions of activity peaks are not completely consistent with Cook (1973), the difference reaches the value between 1 or 2 days. We have found a possible long time variability of the ζ Perseid shower. However its validation needs further observations. The mass separation in ζ Perseid shower is clearly evident. This is only partial in S Taurids and β Taurids showers and no one was recorded in N Taurids. The activity of day-time showers was due to echoes with $T \leq 10 \text{ s}$ while of S Taurids due to echoes having $T \leq 3 \text{ s}$ and in case of N Taurids possessing $T \leq 5 \text{ s}$. This is probably caused by different dynamical history of a particular shower. A clear lack of long duration echoes within all these showers indicating the depletion of massive meteoroids was also found.

Acknowledgements

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RADAR METEORS RANGE DISTRIBUTION AND SOME PARAMETERS OF METEOROIDS: APPLICATION TO ζ PERSEIDS AND β TAURIDS SHOWERS

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Abstract. The theoretical model of a range distribution of overdense radar echoes together with its application to two day-time showers of the Taurid complex is presented. This model provides us with possibility of the estimate of four parameters connected with an the structure of meteor showers and physical features of meteoroids. These are: the mass-distribution index, the shower flux density, the ionization probability and the product of the shape–density parameter and the ablation coefficient. We publish here their values computed from radar data recorded during observations of ζ Perseids and β Taurids in 2003.

Keywords: Meteor showers, physical parameters, radar observations, range distribution, Taurid complex

1. Introduction

Radar observations of meteors can have many aspects. One can count rates of all registered meteors regardless of their characteristics within any prescribed time span. This usually results in an activity profile. Or one can sort observed meteors according to a chosen rule. Such meteors can be divided into various range groups, for example. Then range distribution emerges whose form depends on physical characteristics of meteoroids contributing to it and consequently some physical parameters of these bodies could be accessed from the analysis of such distribution.

The mechanical construction of the Ondřejov meteor radar has been described by Plavcová and Šimek (1960). The method of observations we have employed in 2003 was the same as used during the Leonid campaign (e.g. Pecina and Plavcová, 2004) but with the radiant of a particular shower in the Taurid complex having been followed.

In the case of the Ondřejov radar each echo is characterized by four quantities. These are (1) the time of occurrence of the echo, (2) the time

behaviour of the echo amplitude, (3) the duration of the overdense echo, and (4) the range of the reflecting region of the meteor trail. We can construct range distributions by sorting observed echoes into chosen range intervals and also according to the other mentioned characteristics as an duration, or so. After performing this procedure we can get a graph similar to those in Figure 1.

The range distribution mirrors the fact that meteor trails associated with a particular shower occur in a restricted height interval. The interval depends on the radiant position, on the masses and speeds of meteoroids contributing to distribution and on other physical quantities, which we can describe by means of the ablation coefficient, σ , and the shape-density coefficient, K (e.g. Ceplecha et al., 1998). Since we register during an observation of meteor showers simultaneously many meteors with various masses, their mass distribution characterized by the mass distribution index, s , together with the shower flux density, Θ_{m0} , have an influence upon the shape of their range distribution curve. These quantities are discussed below.

2. Derivation of theoretical model

As a consequence of the fact that the range distribution is a result of the contribution of meteors having various masses, our theoretical model has to be based on the generalization of the well-known mass distribution power law expressed by the equation

$$d\bar{N} = cm^{-s}dm, \quad (1)$$

where $d\bar{N}$ is number of meteors having masses within the interval $(m, m + dm)$ (e.g. McKinley, 1961). Here s is the mass distribution index, which we suppose to be constant inside the whole mass interval we consider and c is a normalizing factor. The law (1) was derived from observations over the large part of the sky. Assuming that it is valid inside any element of the echo plane and also in any sufficiently short time interval, we can generalize it in following way. It is obvious that the larger collecting area and the longer time interval the greater number of meteors we should observe. This results in a more general mass distribution law in the Belkovich's form (Belkovich, 1971)

$$d^3N = c_n m^{-s} dm dS dt. \quad (2)$$

Here dt is the time interval, $dS = R dR d\vartheta$ is the element of the collecting area within the echo plane. R and ϑ are the corresponding polar coordinates (R is the range from the radar and ϑ is the angle measured in the echo plane). To specify the normalizing factor c_n , we employ the definition of the shower flux density, Θ_{m0} , which is a number of meteors crossing the unit surface of the echo plane

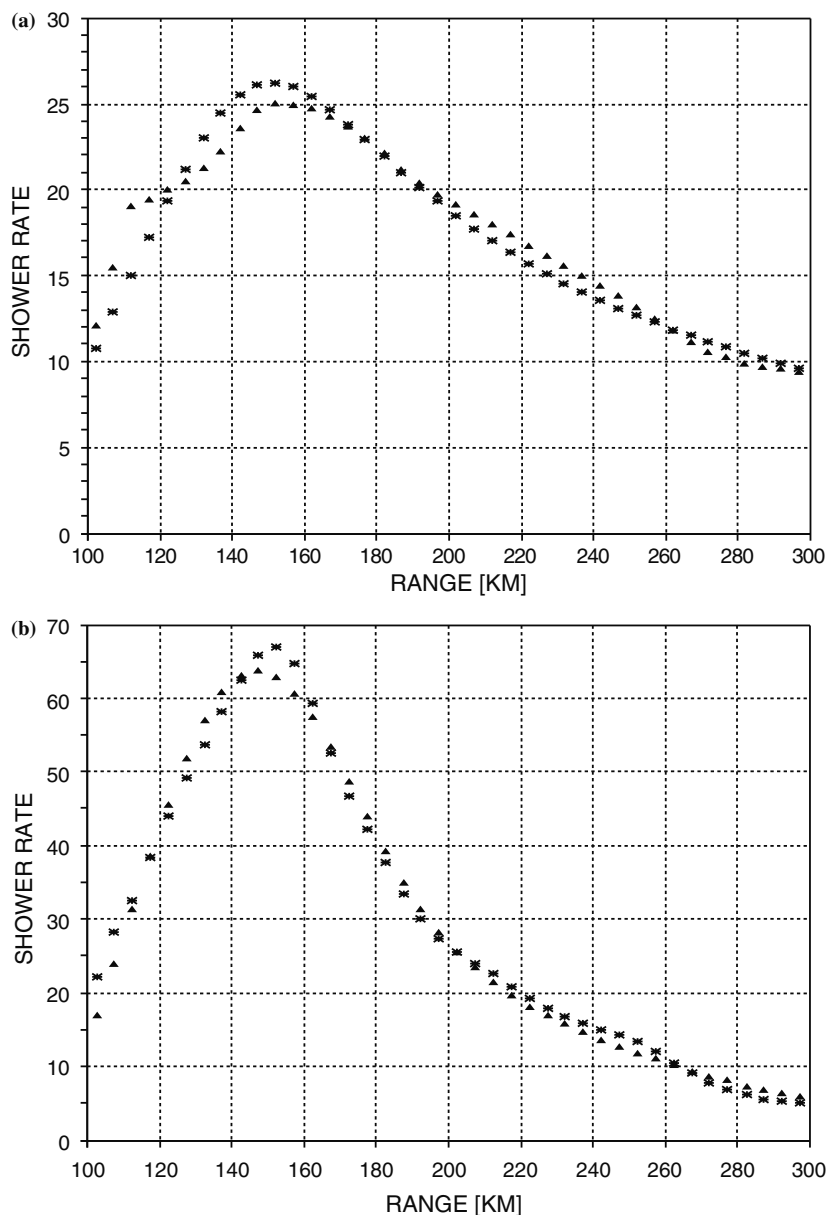


Figure 1. An example of the range distribution constructed from radar meteors of ζ Perseid and β Taurid meteor showers recorded during observations performed within 3–7 UT on 8th June and 4–7 UT on 25th June, in 2003. These histograms comprise overdense echoes with durations between 0.4 s and 10 s. The vertical axis shows shower rates in 5-km-wide range intervals, which are represented by their mid-points on the horizontal axis. All echoes were detected between 100 km and 300 km. The observed range distributions are shown by triangles, the theoretical ones computed using Equation (7), by asterisk (see section 2). (a) ζ Perseids (b) β Taurids.

per time unit having masses in excess of m_0 . This definition together with Equation (2) provides us with the following relation connecting Θ_{m_0} with c_n

$$\Theta_{m_0} = \int_{m_0}^{+\infty} \frac{d^3 N}{dS dt} dm = c_n \int_{m_0}^{+\infty} m^{-s} dm = \frac{c_n}{s-1} m_0^{1-s}. \quad (3)$$

Elimination of c_n between Equations (2) and (3) yields the following important generalized mass distribution power law:

$$d^3 N = (s-1) \Theta_{m_0} m_0^{s-1} m^{-s} dm dS dt. \quad (4)$$

In this equation $d^3 N$ stands for an incremental rate with respect to mass. Since it is better to deal with cumulative rates in practice further, our theoretical range distribution model is based on the cumulative quantity. Thus, integrating with respect to m in (4) we get modified model:

$$\Delta^2 N = \Theta_{m_0} (m_0/m_\infty)^{s-1} dS dt. \quad (5)$$

Here $\Delta^2 N$ is a cumulative number of meteors having masses in excess of m_∞ registered during the time element dt and within the element of the echo plane dS . Θ_{m_0} is related to mass m_0 being an optional constant and m_∞ is the mass of a meteoroid before entering the Earth's atmosphere. Since this quantity is not directly observable we have to transform the above equation to include only observable ones. We chose a duration of an overdense echo T_D , controlled by the ambipolar diffusion only, which can be related to the observed duration, T , we have at our disposal from the data. The link between T_D and T depends on the deionization processes running inside particular meteor trail. We will simply write $T_D(T)$. A desired relation connecting the mass of a meteoroid producing an overdense radar echo with its corresponding duration $T_D(T)$ can be deduced from the physical theory of meteors. Assuming that radar meteoroids do not significantly decelerate we arrive at the link between m_∞ and $T_D(T)$ (e.g. McKinley, 1961)

$$m_\infty = \left([T_D(T) + c]^{1/2} / a\rho(h) + b\rho(h)/\cos z_R \right)^3, \quad (6)$$

where $\rho(h)$ is the atmospheric density which we take in the form $\rho(h) = \rho_0 \exp(-h/H)$ (H represents the scale height, z_R is the radiant zenith distance). The constants ρ_0 and H are assessed by the least-square fit to CIRA (1972) within the heights interval from 80 to 120 km. The constants a, b, c are the following:

$$a = (\lambda/2\pi)(r_e K \sigma v_\infty^2 \beta / \mu D_r \rho_r)^{1/2}, \quad b = HK \sigma v_\infty^2 / 3, \quad c = r_0^2 / 4D.$$

Here λ is the wavelength of the radar wave (8 m), v_∞ is the speed of meteoroids before entering the Earth's atmosphere. Since $D = D(h) \sim 1/\rho(h)$ and

the initial radius r_0 is a function of h , its combination $r_0^2/4D$ in c depends very weakly on height. This fact we neglect. The above formulae contain also the classical electron radius, r_e , the average mass of atom evaporated from a meteoroid surface, μ , and the ambipolar diffusion coefficient D_r , corresponding to the atmospheric density, ρ_r at the height h . The parameters a and b depend on the physical features of meteoroids, i.e. on the product of the shape-density parameter and the ablation coefficient $K \cdot \sigma$, and the ionization probability β . We suppose both these quantities to be the same for all members of a particular shower. When we insert m_∞ from (6) into (5) and perform the integration over the observed time interval as well as over the collecting area of the echo plane we arrive at the principal formula of the model:

$$N = \Theta_{m0} \int_{t_1}^{t_2} dt \int_{R_1}^{R_2} R dR \int_{\vartheta_1(R)}^{\vartheta_2(R)} \left[\frac{\sqrt[3]{m_0} a \cos z_R(t) \rho(h(\vartheta, R))}{\sqrt{T_D(T) + c \cos z_R(t) + ab \rho^2(h(\vartheta, R))}} \right]^{3(s-1)} d\vartheta. \quad (7)$$

The number of meteors depends on s and is directly proportional to Θ_{m0} . The time dependence of (7) is given by $\cos z_R(t)$ of the shower radiant. R_1 and R_2 are limits of the particular range interval following from the definition of the range distribution itself. ϑ_1 and ϑ_2 are bounds of an angular interval within the collecting area of the echo plane computed for chosen R from the radar equation for the overdense type of echoes derived by Kaiser (1961) which we have modified into:

$$P_T(\lambda^2/27\pi^2) \sqrt{D_r \rho_r} \sqrt{T_D(T) + c} \left(G(\vartheta)^2 / R^3 \sqrt{\rho(h(\vartheta, R))} \right) = P_{\min}, \quad (8)$$

when replacing electron line density by the duration $T_D(T)$. Here $P_{\min}$ represents the minimum power recognizable as a meteor echo (2×10^{-13} W in our case). The value of $h(\vartheta, R)$ in (7) and (8) follows from the familiar cosine law of planar geometry:

$$h(\vartheta, R) = (R_E^2 + R^2 + 2R_E R \sin z_R \cos \vartheta)^{1/2} - R_E,$$

with R_E standing for the Earth's radius.

The formula (7) contains of Θ_{m0} , s , a and b as unknown parameters. We estimate them from the least-squares fit of the observed shower rates to theoretical ones by means of Levenberg–Marquardt method (Press et al., 1992). Subsequently we compute the product $K \cdot \sigma = 3b/Hv_\infty^2$ and the ionization probability $\beta = (2\pi/\lambda)^2 (\mu H D_r \rho_r / 3r_e) (a^2/b)$ from known a and b to get quantities having a physical meaning.

3. Application to Day-time Showers

The shower rates of ζ Perseids and β Taurids we registered were rather low. As a consequence the range distributions were not very well defined so that we had to restrict our computations to the only one day in both cases, on which the quality of the data was the highest. This were respectively 8th of June and 25th of June when maxima of activity of these showers were detected (see Pecina et al., 2005). The periods of background and shower activities are presented also there. To discriminate between ranges of these showers having almost identical declination and right ascension differing by 25° we have chosen appropriate almucantar branch in respective case. The discrimination was supported also by the time difference between maxima activity comprising 17 days. To be able to proceed further it is necessary to define the function $T_D(T) = T$. The physical theory of ionized trails yields for the case of attachment the formula

$$T_D = \left(T + \frac{r_0^2}{4D} \right) \exp(a_e n T) - \frac{r_0^2}{4D},$$

where a_e is the constant of attachment and n is the concentration of the molecules to which the electrons attach. For ozone $a_e \simeq 10^{-12} \text{cm}^3 \text{s}^{-1}$ (Baggaley, 1972). Since $T \gg r_0^2/4D$ in case of examined showers and, moreover, $n \simeq 10^9 \text{cm}^{-3}$ at its maximum at 85 km, we can simplify this relation to $T_D(T) = T$. Since the duration of observed overdense echoes did not exceed 10 s we have inserted $T_D = 10$ s into (8) when computing the angular limits $\vartheta_1(R)$ and $\vartheta_2(R)$. Then these limits corresponded to highest possible area limits within which all observed echoes could have been detected. All radar echoes of both daytime showers were recorded between 100 and 300 km. Both theoretical (Equation (7)) and observed range distributions are drawn in Figure 1. The parameters we have arrived at are listed in Tables I and II. We are not able to split K and σ in our model. The possible range of σ under the various assumption on K is given in the last column of Table I. To our knowledge there are no independent values of σ and K yet

TABLE I

Θ_{m0} in $\text{m}^{-2} \text{s}^{-1}$ units and mass distribution index s together with the product $K \cdot \sigma$ as a result of a fit of theoretical rates to observed ones using Equation (7)

Shower	$\Theta_{m0} \times 10^{12}$	s	s'	$K \cdot \sigma \times 10^2$	range of σ
ζ Perseids	15.10 ± 0.98	2.08 ± 0.22	2.45 ± 0.10	0.92 ± 0.24	0.005–0.015
β Taurids	3.53 ± 0.35	2.53 ± 0.55	1.15 ± 0.36	0.73 ± 0.11	0.006–0.018

K is expressed in CGS system of units while σ in units of $\text{s}^2 \text{km}^{-2}$. In the third and fourth columns there are the values of s from our model and s' from the $\log N$ versus $\log T$ fit to give the possibility of their mutual comparison.

TABLE II

Ionization probability β_{rdm} deduced from the range distribution model compared with β_J computed according to Jones (1997) and β_{KLL} due to Kashcheyev et al. (1967)

Shower	β_{rdm}	β_J	β_{KLL}	$v_\infty[\text{km s}^{-1}]$
ζ Perseids	0.0588 ± 0.0080	0.0502	0.1479	29
β Taurids	0.0799 ± 0.0107	0.0728	0.2087	32

published. However, the product restricts the extent of their possible values. Since the shape-density parameter depends on density of a meteoroid we estimated the value of σ for various meteoroid compositions, assuming a spherical body. The results expressing the range of the ablation parameter for most fragile cometary material to material of Geminid type meteoroids are in the last column of Table I. It can be seen that for both daytime showers the range of σ does not differ a lot. Values of s from our model and values of s' from the $\log N$ versus $\log T$ fit are given in Table I.

4. Conclusions

We have presented results of the application of the theoretical model of the range distribution of radar meteors. This model allowed us to compute four quantities connected with the inner structure of meteor showers and with physical features of meteoroids. We have presented these values for the ζ Perseid and β Taurid showers observed in 2003. Even though we have used an approximation of nondecelerating meteors, our values of the ionization probability agree rather well with Jones's probability, see Table II. This is not the case of β computed according to (Kashcheyev et al., 1967). Both values of s following from the model are a bit higher than ones computed from the classical $\log N$ versus $\log T$ fit Pecina et al. (2005). The reason is due to nonequal collecting areas of meteors having different durations (see, e.g. Pecina 1984), which was not accounted for in Kaiser's formula. A small difference between the observed and theoretical distributions in Figure 1 at low ranges are probably due to the fact that we did not take into account the meteoroid deceleration that manifests itself mainly at lower heights and ranges.

Acknowledgements

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ASSOCIATIONS BETWEEN ASTEROIDS AND METEOROID STREAMS

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Abstract. The recent systematic monitoring of the skies has led to the discovery of an increasingly large number of objects on Earth approaching orbits. Not surprisingly, an increasing number of this population have also been associated with meteoroid streams in the literature. We will review the history of this topic. We have also conducted our own search for asteroids moving on orbits that are similar to the orbits of known fireball streams. As NEOs are moving in prograde orbits with low geocentric velocities, any potential streams will have large radiant areas and in consequence, may have been identified as several “sub-streams”. This greatly hampers both their detection and their recognition as single meteoroid streams. With the large number of Near Earth Asteroids detected, the probability of two orbits being similar at the present time by coincidence is high. We have therefore also investigated the evolution of the orbits and only include as real asteroid-stream pairs those where the evolution is also similar over 5000 years. We have identified nine pairs, including the well known pair of the Geminid meteoroid stream and asteroid 3200 Phaethon. Currently there are a number of papers being published on the pairing of asteroid 2003 EH1 and the Quadrantid meteoroid stream. Because of the newness of the research and the fact that this is a high inclination pair, we have excluded this pair from our discussions.

Keywords: Asteroid, Meteoroid streams

1. Historical Review

The notion that some meteoroid showers may be associated with asteroids is fairly old, having first been suggested by Olivier (1925) and Hoffmeister (1937). It is undoubtedly true that some asteroids have orbits that are currently very similar to the mean orbit of some meteoroid streams, asteroid 3200 Phaethon and the Geminid meteoroid stream being perhaps the best-known example (Whipple, 1983). At the current time the association between the Quadrantid stream and asteroid 2003 EH1 is receiving much attention (see Jenniskens, 2004; Williams et al., 2004). This association will undoubtedly pass all the tests that we will discuss later, but, as the work is very recent, it seems unnecessary for us to repeat it. Consequently we will not discuss further the association of the Quadrantids and asteroid 2003 EH1. The recent systematic monitoring of the skies by systems such as LINEAR and LONEOS, principally to identify asteroids that may present a danger to the Earth

has naturally led to a large increase in the number of known Near Earth Asteroids. This increase in number also naturally leads to an increase in the number of asteroids on a similar orbit to meteoroid streams with a consequential increase in the number of asteroids being proposed as parents of meteoroid streams. This is especially true for short period streams near the ecliptic since their inclinations are much more likely to match the inclinations of Near Earth Asteroids.

Over 30 years ago, Sekanina (1973, 1976) identified a number of new weak meteoroid streams by comparing the orbits of faint meteors that had been obtained by the Harvard radio meteor program. He suggested that up to 15 asteroids could be associated with some of these new weak streams, including the suggestion that asteroid 2101 Adonis and the σ Capricornid stream were associated. Other authors suggesting associations of Near Earth Asteroids with meteoroid streams include Drummond (1982), Babadzhanov and Obrubov (1983), Olsson-Steel (1988), Kresák and Štohl (1990), Hasegawa et al. (1992), Ryabova (2002), Babadzhanov (2003), Langbroek (2003) and Terentjeva and Barabanov (2004).

Almost without exception, these claims are based on the present day similarity of the orbit of the asteroid and the mean orbit of the stream. With the large numbers of asteroids that have been discovered, there is a high probability that some orbits are currently similar to those of meteoroid streams by chance.

Comparisons of the orbits are made using either a criterion, usually called the D criterion, formulated by Southworth and Hawkins (1963) or a different version of the same idea, called the D' criterion formulated by Drummond (1981). Both involve calculating the square of the differences between the five orbital elements. A small value of either D or D' implies a small difference, that is, the two orbits are similar. Recently Valsecchi et al. (1999) produced a new measure of orbital similarity, but to date has been little used by meteor astronomers. In any investigation, the author has to make two choices in order to progress, deciding which method is optimal given the differing rates of evolution of the orbital parameters and deciding on the choice of the threshold value for orbital similarity.

Asteroids differ both in structure and composition from comets and so the mechanism of formation of meteoroid streams should also differ. The mechanism of meteoroid ejection from a comet is well understood. Essentially the cometary nucleus (Whipple, 1951) heats up as the comet approaches the sun until a point is reached where the ices sublimate, leading to an outflow of gas. This gas outflow carries the meteoroids with it away from the nucleus. It is clear that this mechanism will lead to meteoroid ejection primarily around the perihelion of the orbit. As ejection velocity is much less than the orbital velocity, there is little change in either the energy or the angular momentum per unit mass and so the meteoroid orbit is very similar

to the comet orbit (see for example Williams, 2002 for a full discussion). The formation of a meteoroid stream from an asteroid requires a different mechanism for the release of meteoroids since asteroids contain little or no ices that can sublimate. Williams (1993) suggested that inter-asteroid collisions were responsible. These can take place anywhere, but close to aphelion (in the main belt) are most likely for two reasons, there are many more bodies to collide with here and the asteroids spend most of their time in this region. Other processes suggested include fast rotation and thermal tension at close perihelion passages. The most recent reviews of the origin of meteoroid streams from asteroids are by Obruchov (1999), Babadzhanov (2001) and Jopek et al. (2002). All of these processes involve events which cannot regularly supply meteoroids into a stream, and it is questionable whether sufficient mass can be lost to produce a recognizable stream.

Öpik (1963) and Wetherill (1988, 1991) have claimed that dormant cometary nuclei make up at least a part of Near Earth Asteroid population and thus a more likely scenario is that the meteoroid streams were formed while the associated body was still an active comet. Support for this view has come from the observations of cometary activity on both 2060 Chiron and 4015 Wilson-Harrington (Meech and Belton, 1989; Bowell, 1992). According to Weissman et al. (1989), the most probable candidates to be dormant comets are 3200 Phaethon, 2101 Adonis and 2201 Oljato.

Jopek et al. (2002) have shown that for almost all the streams with a geocentric velocity, V_g , greater than 37 km s^{-1} the parent bodies are known and that in almost all cases where there is an asteroid associated with a stream, the parent body of the stream is nevertheless an active comet. However at low inclinations, where V_g is small, there are currently only a few comets present (e.g. P/Encke) and it is evident that a sizable proportion of meteoroids must be associated with what are now classed as asteroids, though they may still be dormant comets.

Rather than simply comparing orbital elements, Babadzhanov (2001) calculated the secular variations in these in order to identify meteoroid showers associated with the Taurid Complex of asteroids. He showed that several asteroids can be associated with some meteoroid streams. Babadzhanov and Obruchov (1987, 1992) also showed that a single body can be the parent of a meteoroid stream that can generate more than one shower. It is clear that a shower can be generated at each node of the stream orbit, a clear example being comet 1/P Halley forming both the Orionids and the η Aquarids, but if the orbit of the stream is very close to the ecliptic (thus moving in almost the same plane as the Earth), then at each node both a Northern and a Southern branch could be recognized, giving a potential total of four showers. Secular perturbations causes nodal precession and this can over time increase the number of potential showers associated with a single parent to a maximum of eight. This supports the claim of Clube and Napier

(1984, 1986) and Steel (1995) that the Taurid Complex consists of bodies with a large range of sizes, including large asteroid-like bodies that are extinct cometary nuclei or their fragments many of which have produced meteoroid sub-streams. All of these contribute to the formation of the whole Taurid meteoroid complex.

As we have already stated, most claims are based solely on the orbital similarities of the stream and asteroid. Deciding whether the association is real, or chance, and, if real whether the asteroid is actually the parent requires additional investigations based on reliable high quality observational data. We will attempt this by considering first the orbital similarity question and then the dynamical evolution of the orbits. For this investigation, we have concentrated on fireball meteoroid streams identified from photographic observations, since these consist of large meteoroids. This means that the observational data is more reliable and that their orbits are affected to a smaller degree by non-gravitational effects so that they remain as stream members for a longer time interval. We then search for Near Earth objects (NEOs) that have similar orbits. Also, as NEOs are moving in prograde orbits, they have a relatively low geocentric velocity so that only the larger meteoroids will become visible as 'meteors' when they interact with the atmosphere. The disadvantage of only using fireballs is that it greatly reduces the number of meteoroids observed in a potential stream. The stream will also have a large radiant area which, due to the low number of meteors, may appear to split into several sub-radiants. This hampers both their detection and their recognition as a single radiant (Kresák 1968; Kresák and Porubčan 1970).

2. Associations Between Asteroids and Streams Based on the Similarity of Their Orbits

A search of the IAU Meteor Data Center catalogue (comprising a total of 3518 meteor orbits, Lindblad, 1991) for fireball streams was conducted by Porubčan and Gavajdová (1994). They found 19 previously unidentified streams and concluded that 46% of all bolides brighter than absolute photographic magnitude -3 (1028 meteors) are either members of these new streams or of the 23 previously known streams. Eighteen of the new fireball streams are moving in short period asteroid-like orbits. In this work we are attempting to identify asteroids that might be associated with fireball streams, not streams that might be associated with asteroids. Hence we have restricted the list of asteroids through which we will conduct a search to asteroids that have a close approach to the Earth (a necessary condition for the streams). The mean orbit of the stream was compared to the orbits of Near Earth asteroids using the Southworth and Hawkins (1963) D-criterion initially with a critical value of D of 0.30.

A further restriction was then imposed, namely that during the period when a given asteroid was less than 0.1 AU from the Earth's orbit, the theoretical radiant had to be within $\pm 10^\circ$ (Neslušan et al. 1998) of the meteor shower radiant while the geocentric encounter velocity V_g , had to be within ± 5 km/s of the meteoroid stream velocity. This search found 76 asteroids, associated with most of the 42 fireball streams. This number was considered too large to be meaningfully discussed further and so the restrictions on the definition of orbital similarity was tightened further, principally by reducing the limit on D to be $D \leq 0.12$. This resulted in 26 asteroids being identified, associated with 20 different streams. In Table I we show the associations that satisfy these tighter conditions. The table lists the orbital elements of the stream and asteroid, the location of the radiants and the geocentric velocity.

It is evident from table that a number of very close orbital associations between streams and asteroids exist. It is also evident that in several cases more than one asteroid is associated with a given stream. Thus possible complexes of objects exist which may be regarded as asteroidal streams as argued by Drummond (2000).

TABLE I
Asteroids moving on orbits similar to those of fireball streams

Stream/NEA	α	δ	V_g	q	e	i	ϖ
β Cnc	121	10	15	0.79	0.60	5	198
2002 XR14	116	18	17	0.71	0.63	2	196
Leo-Ursids	155	23	15	0.82	0.65	5	223
2003 YG118	155	30	16	0.81	0.64	8	221
π Virginids	193	3	23	0.56	0.74	6	281
2003 FB5	195	0	25	0.53	0.79	5	287
σ Leonids	178	-8	18	0.71	0.63	4	264
2003 BD44	188	-9	16	0.78	0.60	3	270
2002 CD14	185	-7	16	0.75	0.58	3	269
γ Corvids	183	-15	14	0.87	0.62	5	263
2002 VU94	175	-25	13	0.91	0.57	9	257
ν Ursa Maj	181	35	8	1.01	0.49	7	243
2001 FE90	179	43	8	0.98	0.49	9	243
1998 KJ17	189	41	8	1.03	0.48	9	240
α Scorpids	247	-29	31	0.33	0.88	10	353
2004 BZ74	249	-34	32	0.33	0.89	17	355
θ Oph (N)	272	-17	23	0.57	0.76	5	3
2001 YK4	277	-20	23	0.59	0.78	5	6
θ Oph (S)	276	-28	20	0.65	0.69	3	4
1994 CK1	271	-29	18	0.70	0.63	5	356
α Cap (N)	316	-9	21	0.63	0.73	5	45

TABLE I
(Continued)

Stream/NEA	α	δ	V_g	q	e	i	ϖ
2004 <i>DL1</i>	315	-14	21	0.55	0.69	2	47
2002 <i>CB26</i>	313	-9	23	0.54	0.72	7	45
α <i>Cap (S)</i>	329	-16	22	0.60	0.75	3	54
2004 <i>DF2</i>	327	-21	20	0.58	0.65	5	55
ι <i>Aqr</i>	334	-14	13	0.88	0.65	1	45
2002 <i>TA58</i>	335	-4	11	0.94	0.63	2	50
2001 <i>SP263</i>	331	-6	11	0.92	0.55	2	45
<i>Piscids</i>	16	2	25	0.53	0.82	4	106
2003 <i>SF</i>	14	3	24	0.48	0.78	6	109
2002 <i>HP11</i>	7	-4	24	0.49	0.77	5	100
<i>Taurids (S)</i>	50	13	28	0.36	0.83	6	153
2003 <i>UV11</i>	50	13	26	0.34	0.76	6	157
χ <i>Orionids (N)</i>	82	26	27	0.42	0.82	3	181
2002 <i>XM35</i>	81	26	28	0.38	0.84	3	183
χ <i>Orionids (S)</i>	81	18	23	0.53	0.76	4	173
2201 <i>Oljato</i>	87	20	20	0.62	0.71	3	173
α <i>Taurids</i>	67	16	15	0.76	0.60	3	146
2001 <i>XG1</i>	63	14	14	0.81	0.60	3	138
2000 <i>YA</i>	69	15	14	0.83	0.65	3	144
<i>Dec Aurigids</i>	85	36	20	0.67	0.70	7	168
4183 <i>Cuno</i>	92	36	17	0.72	0.64	7	171
β <i>Perseids</i>	43	42	11	0.93	0.63	7	125
2003 <i>XV</i>	44	32	12	0.86	0.55	5	124
<i>Geminids</i>	112	33	35	0.14	0.90	24	225
3200 <i>Phaethon</i>	116	32	34	0.14	0.89	22	227

The associations shown in Table I are based only on the similarity of the orbits at the current time. Some may be similar by chance as both sets of orbits evolve. To confirm that a particular association is real we also need to consider the orbital evolution of both stream and body.

3. Comparison of the Orbital Evolution of Asteroid and Stream

We have numerically integrated the orbits of all the asteroids listed in Table I and also the mean orbits of the streams as represented by the motion of 18 theoretical meteoroids distributed uniformly in mean anomaly about the stream orbit. The integration period was 5000 years in each case unless clear divergence in behaviour was noted on a shorter time-scale. We have used the

Adams-Bashforth-Moulton 12th order method, with variable step-length. The positions of the planets are taken from the JPL Ephemerides DE406. The influence of non-gravitational forces on test meteoroids was not included in our procedure as well as we do not study resonances here. It is not practical to show the results for all the asteroids and streams, but in Table II we list those associations that have a similar evolutionary pattern so that the orbits of both stream and asteroid are similar for most, if not all, of the time interval. Nine pairs survived this test and additional data for these nine pairs is given in Table II, namely the absolute magnitude of the asteroid and its diameter (assuming albedo of 0.04). Also given is the range in the D value in the time interval and the integration period. The comparison of the orbital evolution for these associations are shown in Figures 1–9. Each figure is composed of four sub figures which respectively show the changes in perihelion distance, eccentricity, inclination and D (the Southworth and Hawkins parameter) against time. In the first three cases, the solid line represents the asteroid while the shaded gray area, the area bounded by the evolution of each of the test meteoroids representing the stream.

4. Discussion of the Results

The bare statistics are interesting. Out of 2836 NEOs known in June 2004, 76 were found to satisfy our initial orbital similarity criteria with meteoroid streams. When the conditions for similarity was tightened, this number dropped to 26. However, when orbital evolution is also considered, this number drops dramatically to only 9 asteroids, each associated with a different stream. One of the associations is already well established, namely the Geminids and asteroid 3200 Phaethon. Four of the new associations in the

TABLE II
Asteroid-fireball stream associations that also show a similar evolution

Fireball Stream	NEO	H	Diameter (meters)	D	Period (years)
Geminids	3200 Phaethon	14.60	7400	0.04–0.14	5000
σ Leo (S)	2003 BD44	16.67	2500	0.09	5000
Leo Ursids	2003 YG118	16.95	2400	0.07–0.16	5000
Dec Aurigids	4183 Cuno	14.40	7700	0.10–0.20	5000
χ Ori (S)	2201 Oljato	15.25	5000	0.12–0.16	5000
η Ursa Maj	1999 FN53	18.40	1200	0.12–0.18	4000
α Tau	2001 XG1	22.59	160	0.10–0.15	5000
χ Ori (N)	2002 XM35	22.96	150	0.04–0.12	1500
α Cap (N)	2002 CB26	26.49	30	0.09–0.25	4000

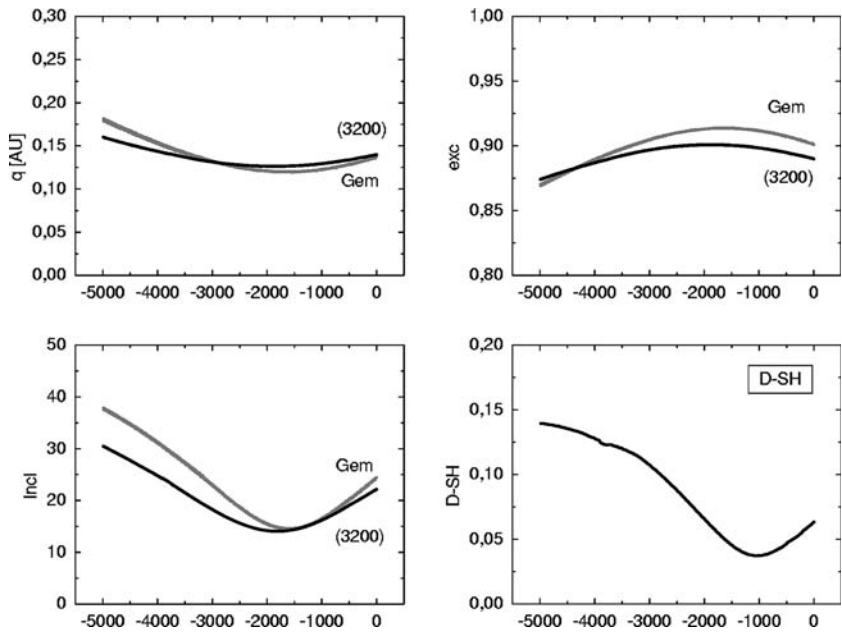


Figure 1. Orbital evolution of Geminids and 3200 Phaethon.

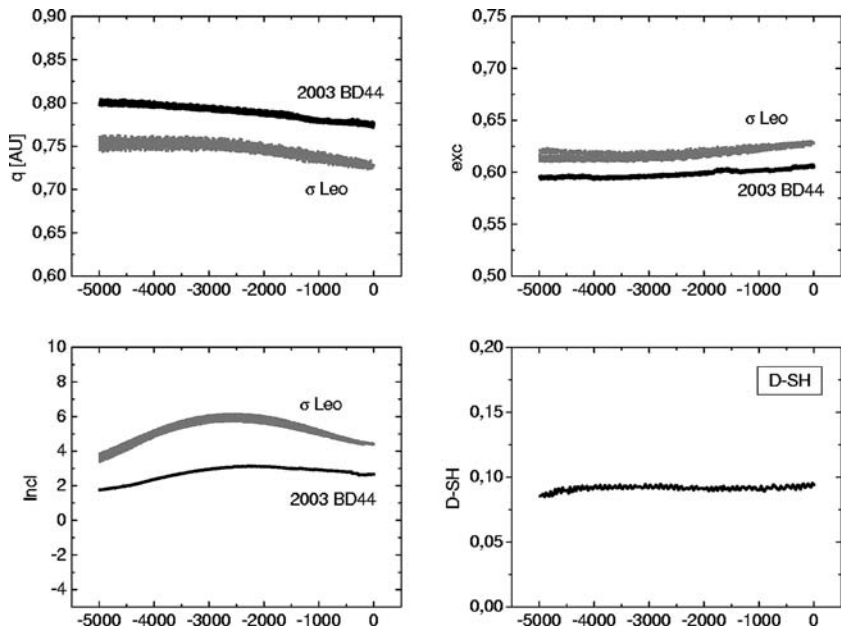


Figure 2. Orbital evolution of σ Leonids (S) and 2003 BD44.

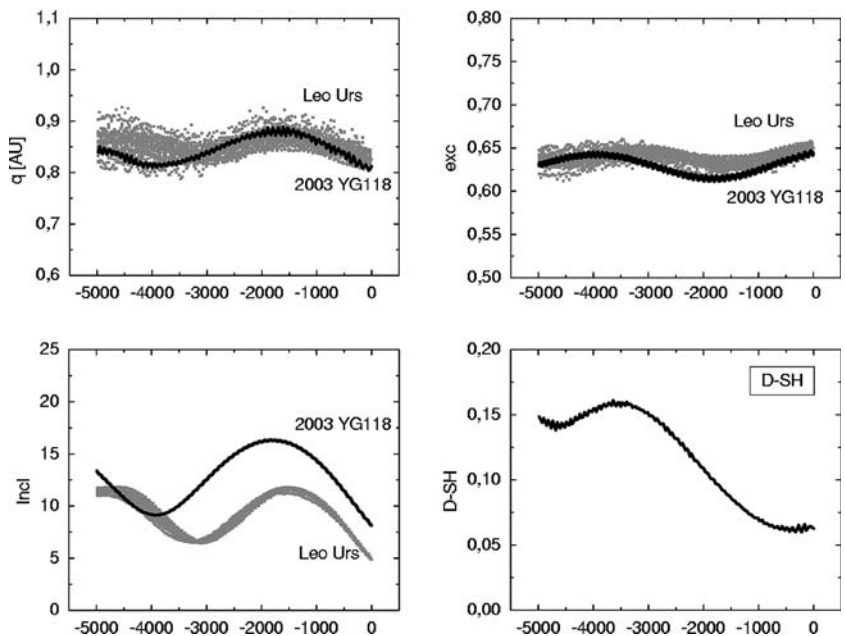


Figure 3. Orbital evolution of Leo-Ursids and 2003 YG118.

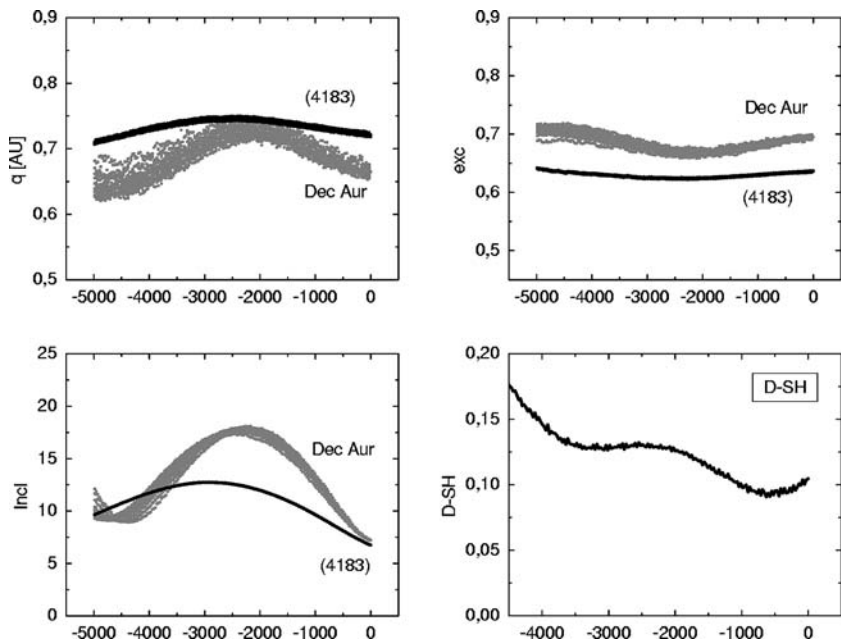


Figure 4. Orbital evolution of Dec Aurigids and 4183 Cuno.

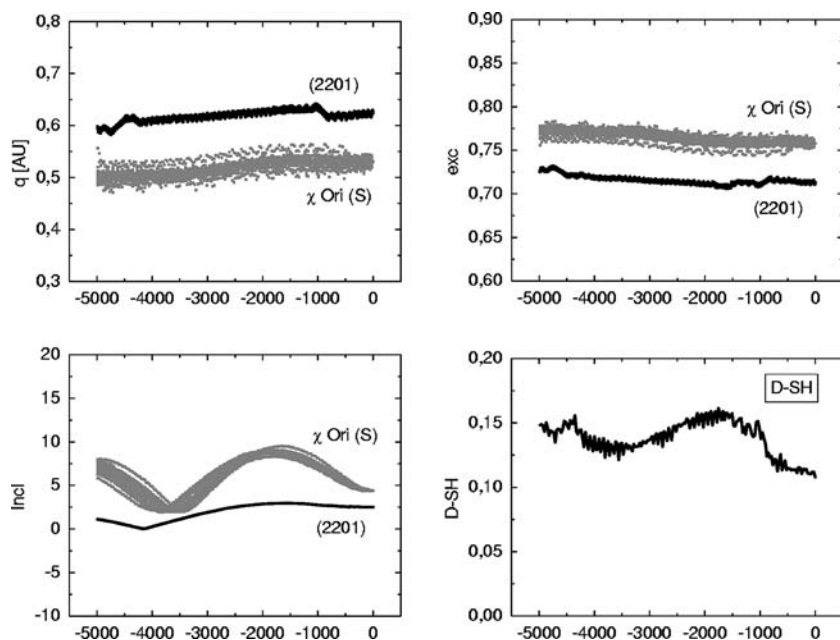


Figure 5. Orbital evolution of χ Orionids (S) and 2201 Oljato.

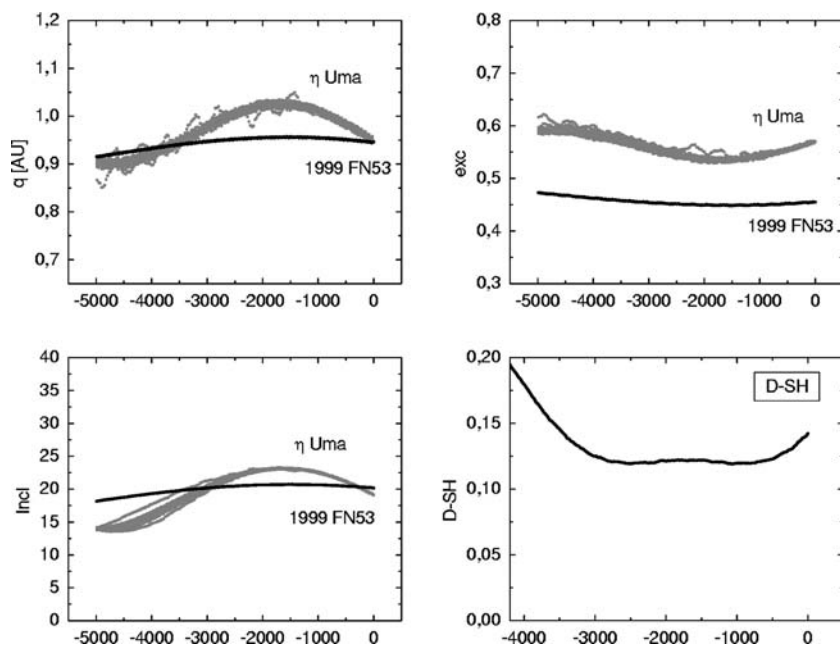


Figure 6. Orbital evolution of η Ursa Majorids and 1999 FN53.

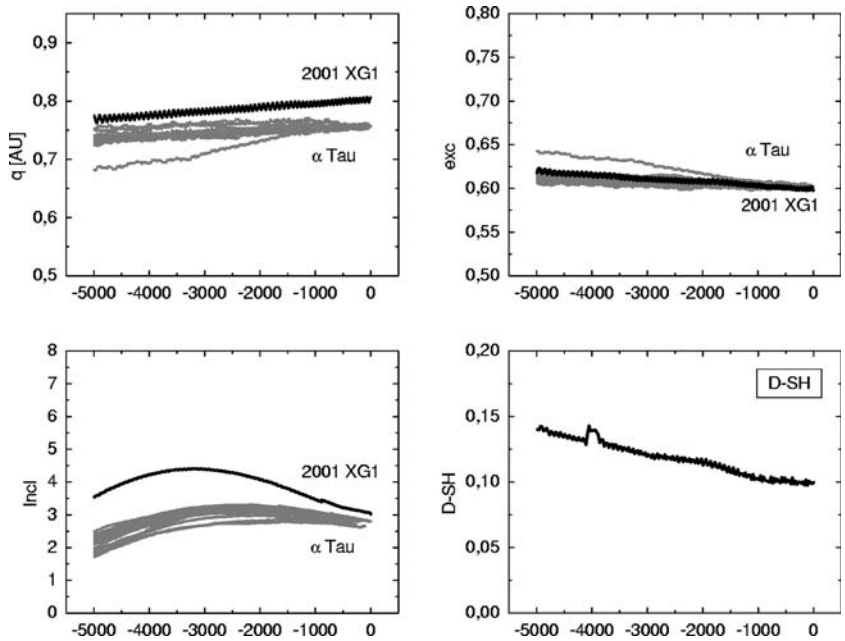


Figure 7. Orbital evolution of α Taurids and 2001 XG1.

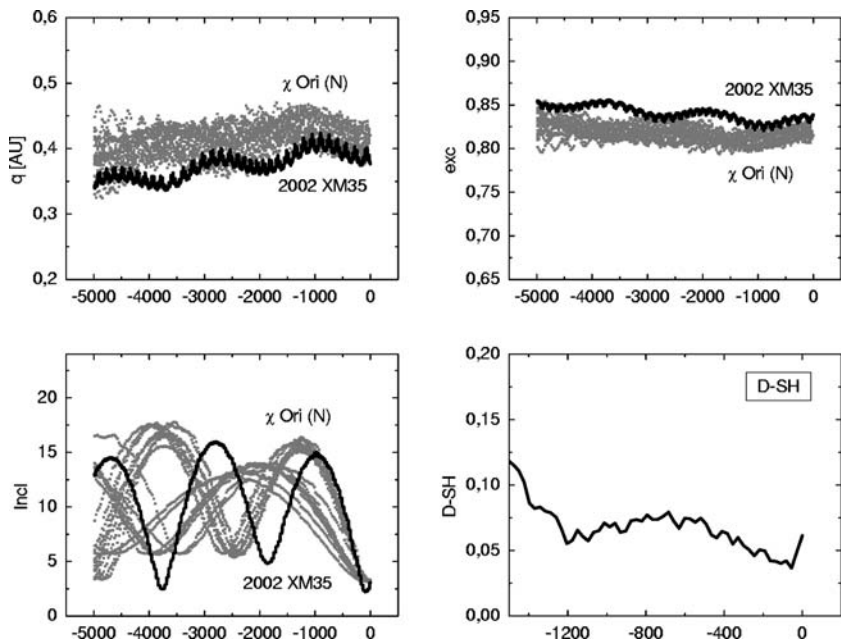


Figure 8. Orbital evolution of χ Orionids (N) and 2002 XM35.

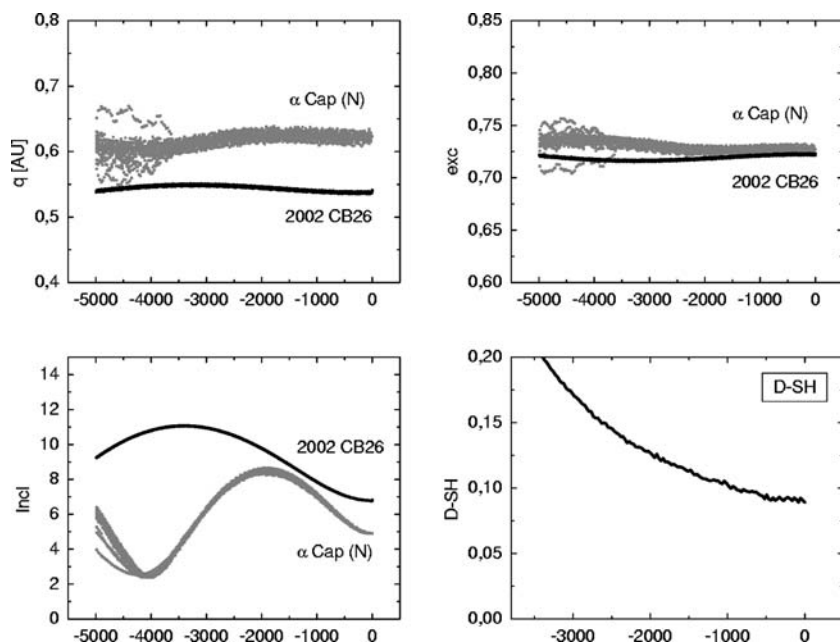


Figure 9. Orbital evolution of α Capricornids (N) and 2002 CB26.

table, σ Leonids (S) and 2003 BD44, Leo-Ursids and 2003 YG118, December Aurigids and 4183 Cuno, χ Orionids (S) and 2201 Oljato, as can be seen from the relevant figures, have an excellent match in the orbital evolution throughout the integration interval. η Ursa Majorids and 1999 FN53 also move on similar orbits for 4000 years but the longitude of perihelia seem to evolve at different rates. This association is also probably real.

Two streams in the table with associated asteroids, α Taurids and 2001 XG1, χ Orionids (N) and 2002 XM35 remain closely associated throughout the time interval (though χ Orionids for 1500 years only, as for longer period the D is high) the evolution in both cases being practically identical. However, in both cases the ‘asteroid’ is small, being less than 100 m in radius. In both cases, a body of several tens meters size should probably be regarded as a large meteoroid rather than an actual parent asteroid.

Finally, we have α Capricornids (N), which appears to be associated with asteroid 2002 CB26. Again, this represents a large meteoroid, but in this case rather than remaining closely associated throughout the integration interval, show a slow approach to the stream for the last 4500 years, with the orbits only becoming similar in recent times.

All the asteroids found to be associated fireball streams are small ($D < 10$ km). From the general study of rotation rates of small asteroids (Pravec et al. 2002), some are binaries on inner-planet-crossing orbits with fast rotation of

primaries. These small asteroids are fragments generated by collisions, mostly with negligible tensile strength (rubble-pile or shattered interior structure). However, asteroids smaller than about 150 m are rotating so fast that they must be a single fragments of the rubble that make up larger asteroids.

5. Summary and Conclusions

Our investigations show that a search for associations between meteor streams and NEOs based on the current time similarity of orbits is not sufficient to establish a generic relationship, many false pairs are found as shown by our orbit integrations. Since integrations need to be performed, the initial orbits need to be well determined so that only good and precise orbits of meteoroids (generally photographic) should be used.

In our search based both on the current orbit similarity and comparable orbital evolution over 5000 years, 9 NEOs moving in the orbits close to the known fireball streams, were found. In addition to asteroid 3200 Phaethon which has previously been associated with the Geminids at least four additional objects may be regarded as potential parents of fireball stream. Four of the 'asteroids' were very small and are more likely to be a large meteoroid or single fragment from the parent body rather than the dormant parent itself.

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SINGLE AND MULTI-STATION RADAR OBSERVATIONS OF THE GEMINID/SEXTANTID METEOR STREAM SYSTEM

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Abstract. The Canadian Meteor Orbit Radar (CMOR) is used to look at the distribution of meteoroids which encounter the Earth. As a single-station operation, it is capable of determining radiant distributions on a statistical basis and the position and speed of individual meteors. The addition of two outlying receiving stations allows the determination of the orientation in space of the meteor leading to an estimate of the orbital parameters of the individual meteor and an independent additional estimate of its speed. Comparison is made of the effectiveness of the two modes of operation using observations on the Geminid and Sextantid meteor streams.

Keywords: Geminid, meteoroid orbit, meteor speed, radar, Sextantid

1. Introduction

The Canadian Meteor Orbit Radar (CMOR) has been operational for a number of years at several locations. It is currently sited near London, Ontario (43.26° N, -80.77° E) and the version described here operates at a frequency of 29.85 MHz. The basic system consists of one transmitting antenna and five receiving antennas at the main site. The receiving antennas are arranged as two orthogonal three-element arrays with a common centre antenna and the others spaced at 2.0λ and 2.5λ , respectively along the respective array axis. This allows the range, elevation and azimuth of the meteor to be determined to within ± 3.0 km and $\pm 1.0^\circ$, respectively. The addition of two outlying receiving stations arranged to form an approximate right angle (96.8°) with the main station at distances of 8.06 km and 6.16 km allows the determination of the orientation in space of those meteors which are 'seen' by all three, about 25% of the total observed at the main station. The signal received on these outlying stations is telemetered back to the main station using UHF links. The three-station layout is illustrated in Figure 1. The main station provides the estimate of the direction (θ , ϕ) and range of

the meteor and an estimate of the speed from the characteristics of the echo, such as the rise-time. If the meteor is observed at all three sites, then measurement of the time delays between the echoes at each out-station relative to the main station, δT_{1m} and δT_{2m} , gives an estimate of the orientation in space of the meteor train and a further estimate of the speed of the meteor. This allows the determination of the orbital elements of the original meteoroid. An example a meteor observed on all three stations is shown in Figure 2; the speed of this meteor was evaluated as 61.9 km/s from the rise-time and 57.9 km/s from the time delays. A fuller description of the system may be found elsewhere (Webster et al., 2004; Jones et al., 2005).

2. Techniques and Results

The essence of the *single-station* radar is that as a back-scatter system, the meteor train is perpendicular to the line from radar to meteor. Since this latter direction is measured with good accuracy, then the radiant of the meteor must be perpendicular to it. However, the orientation of the meteor train is not known so the radiant can be at any point on a great circle subject to that point being above the horizon; the geometry is shown in Figure 3.

Although the radiant direction is not fully known, this orthogonal property can be exploited on a statistical basis. Originated by Morton and Jones (1982), the idea is to increment the count in each small cell on the celestial sphere along the above great circle. Random meteors will be spread out on the celestial sphere but meteors associated with a shower will accumulate at the radiant. In this way, the radiant of a meteor shower can be mapped and its development with time investigated.

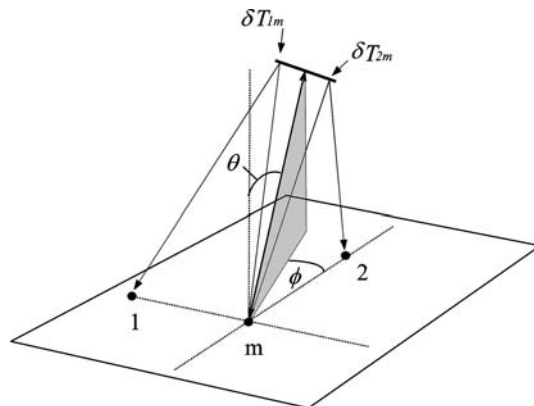


Figure 1. The layout of the three-station system showing the relative positions of the main station (m) and the two outlying stations (1 and 2).

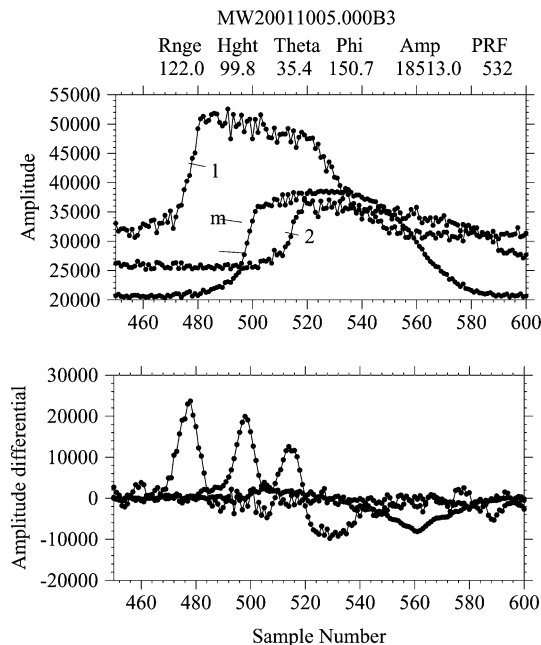


Figure 2. An example of a meteor observed on all three stations (offset for clarity). The amplitude differential is used to determine the delay times (see Webster et al., 2004).

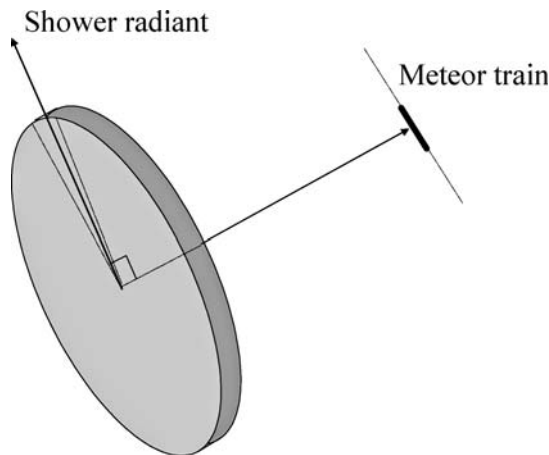


Figure 3. Illustrating the relationship between direction to the meteor and the radiant. The radiant is perpendicular to the direction to the meteor from the radar. An error of $\sim 1^\circ$ in these directions is typical.

In order to determine the radiant and orbital parameters for individual meteors, the position in space and the orientation at the time of observation are needed. The *three-station* system is capable of doing this with some degree of accuracy, the trade-off being accuracy against numbers observed on all

three stations. With the leg lengths quoted above, about 25% of the meteors seen by the main station are also observed on the other two; the accuracy depends partly on signal level but is typically in the order of a degree or two in radiant coordinates.

The result of applying these two techniques, single- and three-station, is illustrated in Figure 4 from observations on the 2003 Geminid shower in December. The grid used is at 1.8° intervals in each direction with an average taken over a circle of radius 3° about each point; the (gray-scale) intensity at each point is a measure of the radiant activity. The position of the shower radiant stands out clearly in both of the presentations with nearly identical coordinates from each. The software developed in this exercise allows the estimation of the coordinates by eye using cross hairs; this leads to value for R.A. and Dec. of $(112.1^\circ, 33.8^\circ)$ from the single station and $(112.8^\circ, 33.8^\circ)$ from the three-station in this example. The difference in appearance in the two is apparent but the agreement in estimation of radiant position is quite good.

Further development in the software allows the automatic estimation of the position of peak activity within the radiant structure and the number of meteors within a chosen angular distance of this peak. The change in radiant position for the Geminid shower over the period 03–17 December 2003 is

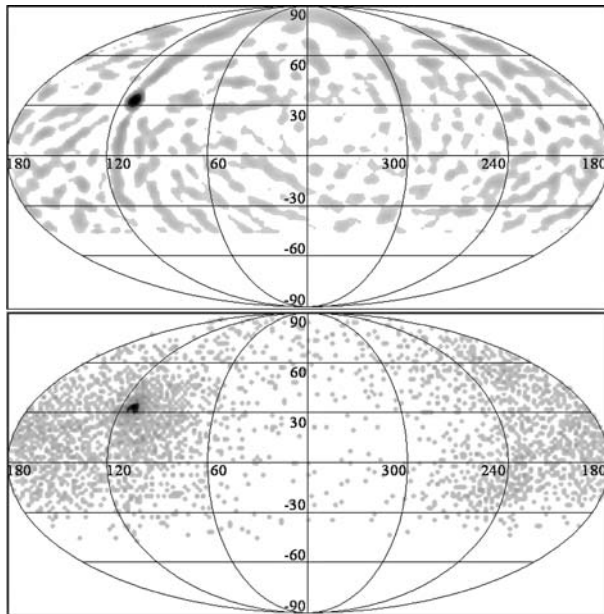


Figure 4. Radiant maps (Right Ascension vs. Declination) produce from observations from the single-station (top) and three-station (bottom) for 14 December, 2003. The Geminid radiant is clearly visible on both. It will be noted that only radiant above declination of $\sim -47^\circ$ are observable from the latitude of the system location.

shown in Figure 5; unfortunately, no data is available for 12 December, close to the nominal peak in activity, due to a power failure. While the coordinates from the two approaches generally agree within about 0.5° , the three-station estimate appears to be consistently higher by this amount; the reason for this is not apparent at this time but may be related to the system geometry. The fluctuations in the coordinates are believed to originate, in part, in the actual structure of the radiant and this is illustrated in the close-up view in Figure 6; the relatively large change in Right Ascension over the two day period is clearly seen, as is the apparent structure within the overall radiant.

The observed number of meteors associated with the Geminid radiant on a daily basis is shown in Figure 7. The numbers from the single station data are about three times those from the three-station, so the ordinate scale has been adjusted to facilitate direct comparison. The match between the two is very good further confirming that the two approaches give consistent answers remembering that they are significantly different in principle. The peak in activity on the 13 December followed by a steady fall in activity over a few days is consistent with previous observations. Less well established is the behavior before the main peak, where a minor peak in activity is apparent on 9 December. This early activity has been reported in the past (Webster et al., 1966) and is likely related to the structure of the meteor stream and its development over time.

So far, results from observations in December have been considered and these are related to the Geminid shower, a night-time phenomenon. Earlier in the year, the Sextantid day-time shower bears a striking resemblance to the Geminids and both are believed to be related to the asteroid Phaethon (Babadzhanov and Uberov, 1987); this asteroid was discovered in 1983

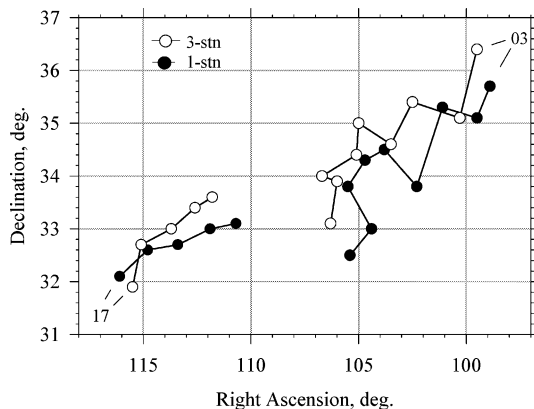


Figure 5. Radiant coordinates of the position associated with Geminid peak activity from the two systems. The observations are for consecutive days between 03 and 17 December 2003, excluding 12 December.

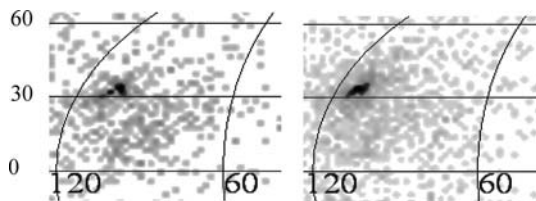


Figure 6. A close-up of the observation of the Geminid radiant using the three-station data for 11 December 2003 (left) and 13 December 2003 (right), illustrating the structure and movement of the radiant.

(Davies et al., 1984). The orbital elements of these are shown in Table I. As can be seen, the relationship between the current Geminid stream and the asteroid is very close, while some of the elements of the Sextantids relate to those of the asteroid.

Figure 8 shows representative orbits of the two streams with the positions in space at 1 a.u. from the sun. As is apparent, the orbit of the Geminid stream intersects that of the Earth in December as an in-bound night-time phenomenon, while the Sextantids appear in early October as an out-bound day-time occurrence. These current positions in solar coordinates are also shown in Figure 9 along with those for the asteroid over the past 20,000 years based on the values presented by Babadzhanyan and Ubersov (1987). Though not exact, the movement of the latter is suggestive of a relationship between the three entities.

As a further indication of the possibility of a relationship between the two meteor streams, Figure 10 show the activity of the Sextantids in late

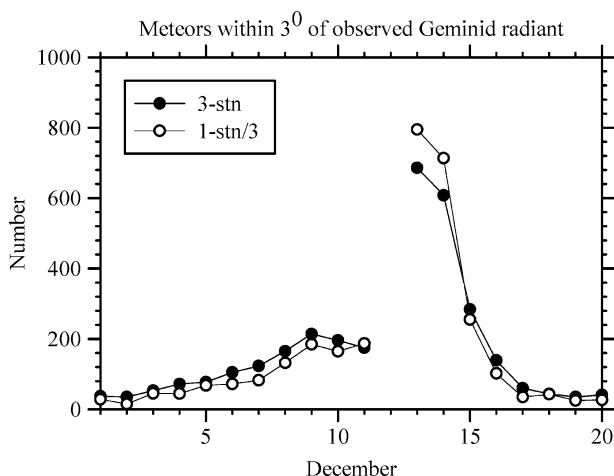


Figure 7. The number of meteors associated with the Geminid radiant observed using the two techniques; the number associated with the single station has been reduced by a factor of 3 to facilitate comparison. Data for 12 December is unavailable.

TABLE 1
Orbital elements of the Geminid and Sextantid meteor streams and the asteroid Phaethon

	Geminids	Phaethon	Sextantids
Perihelion, q	0.140 a.u.	0.140 a.u.	0.16 a.u.
Inclination, i	23.9°	22.0°	22.0°
Eccentricity, e	0.896	0.89°	0.87
Semi-major axis, a	1.4 a.u.	1.27 a.u.	1.23 a.u
Long. Asc. Node., Ψ	261.2°	265.00	3.6°
Argument of perihelion, ω	324.3°	321.7	213°
Right ascension	113°		152°
Declination	$+32.0^\circ$		0.0°
Maximum activity	13 December (night)		3 October (day)

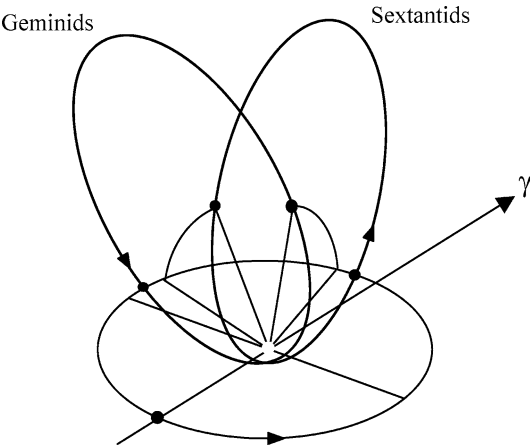


Figure 8. Representative orbits of meteoroids associated with the Geminid and Sextantid streams. The positions at 1 a.u. are as indicated.

September to early October, 2003. The general characteristics, including the early peak and the decay in activity over a relatively few days after the main peak, bear a strong resemblance to the Geminids in Figure 7. The significantly fewer meteors will be noted.

3. Discussion and Conclusions

The basic five-antenna single-station version of CMOR provides valuable information on the activity of the general meteor complex and is capable of determining the position in space of individual meteors. From this the overall activity on a daily basis can be determined and an accurate statistical esti-

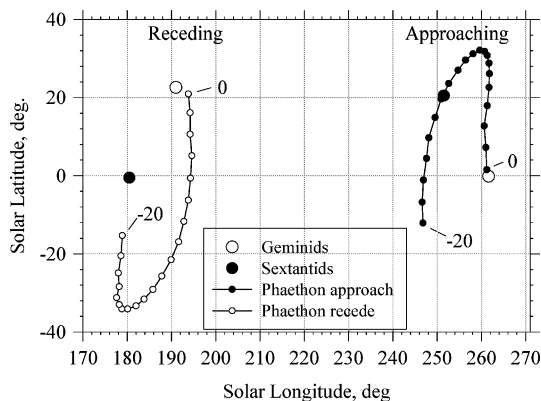


Figure 9. The solar coordinates at a distance of 1 a.u. from the sun of typical Geminid and Sextantid meteoroids. The corresponding values for Phaethon from the present time to 20,000 years ago (0 to -20) are as indicated.

mate of the occurrence and radiant coordinates of meteor showers can be ascertained. This allows the consideration of the development of the meteor streams themselves from the observed movement in, and the structure of, the radiant. The system is relatively straightforward to operate and a number of such systems are in operation world-wide.

The addition of the two outlying stations is unique to this kind of system and gives an added dimension to the observations. Orbital parameters of individual meteors are accessible and a more detailed picture emerges. While this system is more complicated and needs more attention at the operational level, the added information is of considerable significance and allows a more detailed investigation of the meteor complex.

The data presented here takes a look at the relationship between the Geminid and Sextantid meteor streams and the asteroid Phaethon and shows

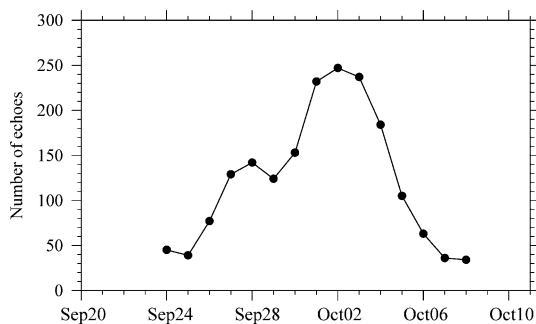


Figure 10. The activity associated with the Sextantid meteor shower in 2003.

sufficient promise to encourage further observational and theoretical investigation. This is being actively pursued at the present time.

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ON THE FUTURE PROSPECTS OF METEOR DETECTIONS (INVITED REVIEW)

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Abstract. The successful application of modern observing techniques for Leonid storm observations show that meteor (shower) detections will have a bright future if the field will pursue difficult but important questions. How to forecast a satellite threatening meteor storm? What happens to the organic matter in meteors and can this be an important source of prebiotic molecules? What range of variations in composition and morphology exists among cometary grains and what does this tell us about the origin of the solar system? What long-period comets approach Earth orbit and can meteoroid streams provide early warning for giant impacts? What are the sources of interstellar and interplanetary grains? Just to mention a few. To answer these questions will need new technologies and facilities, some of which are being developed for other use. This may include NASA's Stratospheric Observatory For Infrared and sub-millimeter Astronomy (SOFIA). In addition, big-science space missions can drive the field if meteor detections are an integral part. Special events, such as meteor outbursts and the "artificial meteor" from the reentry of sample return capsules from interplanetary space, can mobilize observing and theoretical efforts. These and other future opportunities are briefly discussed.

Keywords: Astrobiology, atmospheric sciences, meteor, meteor astronomy, meteor observations, meteor shower, missions, planetary sciences, reentry, sample return capsule, satellite

1. Historic Drivers for Meteor Research

Future trends in meteor research can perhaps be predicted from the science themes that drove past research. The search for shower-parent body associations has been a strong driver, ever since meteor showers were discovered and their link to comets (and asteroids) established (e.g., Schiaparelli, 1867; Porter, 1952; Jenniskens, 2005). New streams were discovered first from visual observations and later from photographic and radar orbit surveys. The space age created the need for understanding the natural meteoroid impact environment for orbiting satellites and the terrestrial mass influx (Öpik, 1956; Hawkins and Upton, 1958; Ceplecha, 1992; Love and Brownlee, 1993). The recent Leonid meteor storms have raised interest in the danger to satellites by meteoroid streams (Beech et al., 1995; True et al., 2000). While most impacts are due to small meteoroids, large mm–cm sized meteoroids are the more

dangerous. They approach Earth from distinct directions, making late stages of meteoroid stream dynamics important as well (McBride, 1997; Jenniskens, 1999). Meteoroid orbit surveys added to understanding the sources and sinks of dust in the zodiacal cloud, a (secondary) topic of several space missions (Lovell, 1954; Jenniskens, 1998; Grün et al., 2001). Upper atmosphere research realized the importance of meteors not only as tracers of air density (Lindemann and Dobson, 1922) and winds (Manning et al., 1954) in the upper mesosphere and mesopause, but more recently also as sources and sinks of the meteoric metal atoms in the neutral atom debris layer, and of energy, solid particles, and electrons, with potential links to noctilucent clouds, airglow, and lightning phenomena (e.g., Murad and Williams, 2002; Plane et al., 2003). This layer couples the warm mesosphere to the thermosphere of Earth. Finally, the cold war and its aftermath led to nuclear treaty monitoring, resulting in the detection of large bolides (Revelle, 1976). This then ties in to the recent searches for potential Earth impacting bodies (Morrison, 1992). The potential to characterize those asteroids and comets has driven the recovery of meteorites from known interplanetary orbits (Ceplecha, 1961; McCrosky et al., 1971; Halliday et al., 1981) and, more recently, the spectroscopic and morphological characterization of meteoroids. Meteor research has also benefited and supported the study of physical conditions in meteors and the development of thermal protection materials for reentering vehicles (Öpik, 1958; Bronsthen, 1983), meteoroid impact protection for spacecraft (Whipple, 1947), planet protection against exogenous microbes, and the origin of life (Thomas et al., 1997; Jenniskens et al., 2000a).

2. Recent New Capabilities

The recent Leonid storms have led to the deployment of a wide range of new technologies for the study of meteors (Jenniskens and Butow, 1999; Jenniskens et al., 2000b; Jenniskens and Russell, 2003; Jenniskens, 2003). They include the use of lidar for measurements of neutral atom debris trails of meteors, leading to the realization that the composition of metal atoms in the wake of meteors is rarely chondritic (Von Zahn et al., 1999; Chu et al., 2000; Von Zahn, 2001). This technology has the promise of measuring the amount of neutral atoms ablated of a given meteor and thus understand how much is not atomized (Jenniskens, 2005). High aperture radar has detected the ionization generated by 10–100 μm sized meteoroids, providing access now to the orbital element distribution of the grains that impact satellites most frequently (Meisel et al., 2002; Hunt et al., 2004). Meteor wind radars (and forward meteor scatter) have become more common and are now providing a continuous watch on meteor activity (e.g., Ogawa et al., 2002; Latteck, 2004).

Cooled CCD detectors have revolutionized the field of meteor spectroscopy and imaging (Yano et al., 2003; Schmidt, 2004). Spectroscopic techniques have become quantitative and the first measurements have been made in the far-UV (Jenniskens et al., 2002; Carbary et al., 2004), the near-UV (Rairden et al., 2000; Abe et al., 2005), near-IR (Jenniskens et al., 2004a, b), and Mid-IR. Mid-IR spectroscopy is still in its infancy, but it has been demonstrated that organic matter in meteoroid trains can be detected (Russell et al., 2000). Submm spectroscopy has the potential to monitor the creation and destruction of small molecules in the upper atmosphere due to meteor activity (Despois et al., 2000). *In-situ* mass spectroscopy of aerosols has shown evidence of nm-sized products of meteor ablation (Cziczo et al., 2000). Rocket experiments are attempting to capture this recondensed vapor. Low cost digital cameras, camcorders, and low-light TV cameras are making a big difference in the detection of multistation meteors and fireballs (Jenniskens et al., 2000c) and the recovery of meteorites from known orbits (Brown et al., 1994; Borovicka et al., 2003). The internet has facilitated rapid communication and data exchange, and a commercial interest in the recovery of meteorites.

Finally, computing capabilities are exponentially increasing and have come to the point where multi-particle problems can be addressed. This has created a leap forward in the field of meteoroid stream dynamics, with non-interacting particles in the changing gravity field of the solar system (e.g., Vaubaillon and Colas, 2005; Jenniskens, 2005), and the study of physical conditions in meteor wakes and trains involving interacting particles in rarefied flow and the Earth's magnetic field (e.g., Boyd, 2000; Popova et al., 2000; Dyrud et al., 2001).

3. Future Drivers of Meteor Research

It is likely that future research will continue to be driven by these overarching science themes, although other topics may gain importance. Many new technologies have only found their first application. In particular, the field of meteor spectroscopy (tracing the fate of meteoric organic matter), lidar studies tracing the fate of metal atom debris, meteorite recoveries from known orbits, and efforts to collect recondensed vapor and other products of meteor ablation, have a bright future.

The most important milestone reached is that half of the Near Earth Object population has been discovered, with a long list of potential Earth impactors now on record (Binzel et al., 2004). This increases the importance of *astroplanetology*, the characterization of the main element composition, mineralogy, and morphology of these minor planets. It now appears possible to understand where all large (diameter >1 km) objects are and what they are

made of. Meteorite recoveries and meteor shower spectroscopy can play a role in this, especially where it concerns minor bodies that are copious producers of dust. Interestingly enough, it is the bodies that are potential meteor shower parents that are among the most dangerous. The origin and evolution of these minor planets is of consequence, which can sometimes be traced by the debris left in their wake that causes meteor showers on Earth. Long-period comets will continue to be an enigma, but those that visit most frequently may be recognized in advance from their 1-revolution dust trails (Jenniskens et al., 1997; Lyytinen and Jenniskens, 2003).

Much of this work will involve space missions to visit the most dangerous objects. In the future, less dangerous, but more frequent, meter-sized near-Earth objects that cross the Earth–Moon system may be visited by micro-satellites, the smallest of which have the best likelihood to impact Earth. This will cause an increased interest in the study of bright fireballs and other work to characterize this otherwise hard to observe population of objects.

4. Opportunities – Space Missions

Space missions are driven in part by the availability of support for big science. A single mission, even a relatively small effort such as the Leonid Multi-Instrument Aircraft Campaign, can mean a great boost for our field. Meteor research has traditionally benefited from minor body missions such as Giotto and the Vega missions to comet Halley (Newburn et al., 1991). Ongoing missions are the NASA Deep Impact comet geology mission, ESA's Rosetta comet lander mission, and the JAXA Hayabusa (formerly MUSES-C) asteroid sample return mission. Future missions may include a replacement for the failed COUNTOUR (Cochran et al., 2002). These missions focus attention on the physical properties of cometary and asteroidal dust. Meteor observations uniquely address large mm–cm sized grains that are not normally encountered in the *in-situ* missions. They can also help create a better understanding of what circumstances will be encountered in the near-comet environment and after landing. In addition, meteor shower investigations can expand the sample of comets for which main-element compositions are available.

The ongoing Ulysses and Cassini missions have meteoroid detectors, as will the future Dawn mission to Ceres and Vesta, and the New Horizons mission to Pluto. These missions continue to benefit from meteoroid orbit surveys that can help illuminate the sources of small meteoroids, including interstellar grains.

In atmospheric sciences, there have just been several missions launched that study the mesosphere and lower thermosphere, in particular the metal atom debris layer and the natural airglow. Limb-scanning spectrometers

measure vertical abundances of small atmospheric molecules, abundances of which may be affected by meteor activity, as well as meteoric metal atom absorptions (e.g., Aikin et al., 2004). NASA's Upper atmosphere Research Satellite (UARS), launched in 1991, was designed to study the upper regions of the atmosphere where sounding balloons and airplanes cannot reach. UARS still has several working instruments. The Halogen Occultation Experiment (HALOE) on UARS measured vertical profiles for atmospheric composition. On April 21, 1995, the European Space Agency launched the Global Ozone Monitoring Experiment (GOME) aboard the second European Remote Sensing satellite (ERS2). More recently, NASA's Stratospheric Aerosol and Gas Experiment (Sage III) on the Russian METEOR-3M mission was launched on December 10, 2001, and also provides profiles of molecular abundances from solar and lunar occultations. NASA's Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission was launched on December 7, 2001, and is also ongoing. It, too, was particularly designed to study the Mesosphere and Lower Thermosphere/Ionosphere region. NASA's Earth Observing Satellite Aura (EOS Aura) was launched on July 15, 2004, and measures atmospheric trace gasses. In 2002, the European Space Agency launched a large environmental monitoring satellite named Envisat, with an occultation experiment "Scanning Imaging Absorption SpectroMeter for Atmospheric ChartographY" (SCIAMACHY). Recently, ESA's ODIN satellite has provided vertical profiles of molecular abundances in the upper atmosphere from sub-millimeter emissions. The validation and interpretation of these satellite data can be a source of support for meteor research and lead to much new insight.

Future missions include NASA's AIM (Aeronomy of Ice in the Mesosphere), particularly designed to study polar mesospheric clouds. Meteoric metals are thought to play an important role in the formation of such clouds. Meteor studies may help answer why they form and why they are changing.

5. Future Capabilities for Meteor Research

Future capabilities for meteor research include technical facilities that are being built and new technologies that are being developed for other applications. Of interest is the potential use of the International Space Station for spaceborne UV spectroscopy (Nuth et al., 1986). Within range now seems to be also the use of private industry space vehicles for the study of the upper atmosphere.

The Stratospheric Observatory for Infrared and submm Astronomy (SOFIA) will be assembled in early 2005 and in operation a year later. This B-747 aircraft has an upper deck that can be developed into a research facility (SOFIA Upper Deck Research Facility, SURF) for serendipitous airborne

astronomy, of great potential use in meteor research (Jenniskens et al., 2004c). A workshop to investigate this opportunity was organized in June of 2004.

In the meteor field itself, technologies are being developed for rapid pointing ("AIM-IT") to facilitate high-resolution meteor spectroscopy, fully automated all-sky camera networks for meteorite recoveries, and interactive tools for automated meteor detection on video and meteoroid orbit calculations from optical observations. Of particular interest is the expanding use of small low-light level security cameras and the more common application of cooled CCD cameras.

Among numerous new technologies of interest outside our field is the orthogonal transfer array (Burke et al., 2004) used in the future PanSTARRS project, a four 1.8-m telescope project of the University of Hawaii in collaboration with MIT Lincoln Laboratory for the detection of minor planets (Kaiser et al., 2002). The array used is a 1 billion pixel CCD that is read out in only 3 s. Each month, the whole accessible sky will be observed three times in 30–60 s exposures at 0.3'' spatial resolution with 6000 square degree coverage per night. Many meteors will be detected in this survey and many small asteroids, perhaps even those that impact Earth. The new CCD technology is important, too, because it can adjust its focal plane position to star scintillation in real time, permitting the use in airborne applications, for example.

NEO searches will likely be extended to include smaller objects (Stokes and Yeomans, 2003; Raymond et al., 2004), gradually diffusing the boundary between meteoroids and minor planets. Where there is overlap, a small meter-sized asteroid predicted to hit Earth, meteor studies of the fireball can help recover the meteorites and tie asteroidal taxonomy class to meteor fireball and meteorite properties.

6. Special Events

The power of special events to drive meteor research has been demonstrated by the Leonid storms. Other showers will show unusual meteor activity in the coming years, some resulting in quite spectacular showers. For example, the 2007 September 1 Aurigids (Lyytinen and Jenniskens, 2003) and the May 31, 2022, tau-Herculids (Lüthen et al., 2001) are expected to peak at or close to storm levels.

Other events that can play the same role include the reentry of sample return capsules of the Genesis, Stardust, and Hayabusa missions (Desai et al., 2004). Those reentries offer an opportunity to study the physical conditions and chemistry in the shock layer of meter-sized asteroids entering Earth atmosphere at hypervelocity speeds. The Genesis return was the first to be

observed as a concerted observing campaign on September 08, 2004 (Jenniskens et al., 2005). The reentry successfully calibrated infrasound sensors for the detection of natural bolides. Measurements of surface temperature were obtained that confirm a low level of radiative heat flux for slow ~ 10 km/s entries. A more interesting (faster) reentry will be that of the Stardust SRC on January 15, 2006, and Hayabusa in June of 2007. Other missions will follow, culminating in the crew return vehicles from missions to the Moon and Mars. Space travel is not without danger and these reentries will help test thermal protection systems under natural conditions.

7. A Meteor Mission

The huge public interest in meteors brings within reach, perhaps, a space mission with an integral meteor observing part. An important science question that could drive a space mission is the unknown carbon abundance in mm–cm sized meteoroids, most readily detected from meteor emissions by spaceborne UV or mid-IR spectroscopy. This calls for a dedicated meteor observatory in space. Such mission can also prepare for the day that meteor showers will be observed on other planets. Only a dedicated experiment can translate meteor observations in answers about the presence and physical properties of large dust grains and their parent bodies elsewhere in the solar system, and the ablation of meteoroids and deposition of organic matter in atmospheres more typical of that of the early Earth.

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