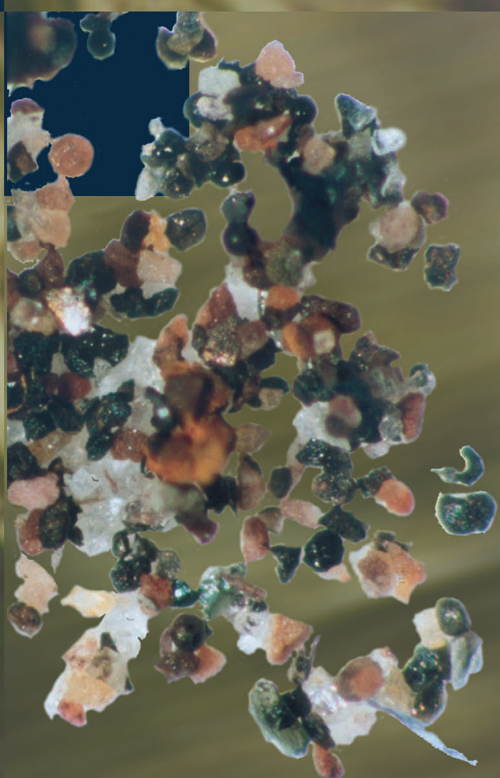
M. Maurette

Micrometeorites and the Mysteries of Our Origins



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Michel Maurette

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Preface

From cosmic dust to the birth of life. This book is purposely not a conventional monograph about either interplanetary debris captured by the Earth (i.e., meteorites and micrometeorites), the very thin ∼100 km-thick shell dubbed as atmosphere that tops our blue planet, and where life is thriving, or the astonishing role of the Moon and Jupiter in our origin. It is rather an extended cross-disciplinary research report about a chaotic cosmic "detective" investigation conducted by our team with the help of a few colleagues, who could foresee the interest of micrometeorites to tackle the opaque mystery of the first ∼500 Myr of the solar system history.

One major objective is to show how we strengthened a qualitative suspicion about the role of the accretion of volatile-rich micrometeorites similar to those recovered from recent Antarctica ices and snows in the formation of the air and oceans of our blue planet. This is an important problem because without water there would be no life, as we know it. For this purpose, a scenario coined "EMMA" (Early Micrometeorite Accretion) was slowly extirpated from a set of confusing data buried in the flow of details usually given in most papers (including ours). Other objectives were to assess the role of juvenile micrometeorites in the prebiotic chemistry that led to the birth of life, and their potential as "probes" of early solar system processes, including the formation of the solar system, the early history of comets, the post-lunar greenhouse effect on the Earth that was the only one to be effective in the origin of life, etc.

We had to navigate out of sight on chaotic, cold and beautiful adventures where we met successively:

– the harsh conditions of the superb Antarctic and Greenland ice sheets, where we collected (in spite of the noisy disapproval of Adélie penguins during our first attempt in Antarctica in 1987) large unmelted micrometeorites with sizes of about 100 µm;
– the difficult handling of these micrometeorites, which required their fragmentation into several pieces without loosing them (i.e., a typical mission "impossible"), with the view of conducting several distinct destructive analyses of the same micrometeorite;
– their difficult analyses frequently conducted at the limit of sensitivity of the most powerful techniques of microanalyses (i.e., when you claim with the

greatest arrogance that this damned weak signal can be reliably extirpated from its terrible host background);
- the comparison of these micrometeorites with the ∼135 groups of meteorites known at this date, which forced us to be kinds of first year students (at least until to morrow) in "Meteoritics" under the guidance of Gero Kurat;
- a stunning "chaos" in the mineralogical, chemical and isotopic compositions of meteorites which is not fully understood;
- several distinct bold intrusions in the friendly world of exobiology where we did not even know about the meanings of the basic letters of the alphabet of this discipline, such as AIB, glycine and peptides, and which were (hopefully) partially successful through the patient and enthusiastic guidance of André Brack;
- authoritative and impressive predictions of models that all rely on hidden adjustable free parameters, which have to be painstakingly identified as to reject courageously, in the greatest loneliness, some models still quoted in the literature as "elegant", and which are understood by half a dozen experts around the world.

Fortunately, in addition to the Antarctica and Greenland ice sheets, we also met other fascinating beauties such as:

- shooting stars;
- the superbly craterized Moon (that unexpectedly became a "star" in our model);
- the giant Mars-sized body that formed the Moon during its cataclysmic impact with the proto-Earth, and which was on the verge of destroying our baby planet still to become blue;
- the late spike of impactors that formed the 12 large lunar impact basins with diameter ranging from 300 to 1300 km, on the near-side of the Moon, about 3.9 Gyr ago;
- the other inhospitable terrestrial planets (Mars, Venus, Mercury);
- Jupiter, the largest of the giant gaseous planets, which behaves as a gigantic sling firing cosmic projectiles to the Earth;
- asteroids, and comets qualified of small bodies and which have a terrifying killing power;
- the dusty faint enigmatic zodiacal cloud;
- the early dusty solar nebula and its mysterious "x-wind";
- the dusty stellar "nurseries" where stars are simultaneously born;
- the reviewers, who rejected our papers with the concise and useful statement that they are "*not convinced by the authors";*
- beautiful books and challenging papers edited and/or written by a few colleagues who have still a passion for science.

Overview of a cosmic detective investigation. In our investigation "hydrous-carbonaceous" micrometeorites and meteorites turned out to be major witnesses of the mysteries of our distant past. For the first time, they will be on a par in a book written in English, and their close association will be maintained up to the last final section. They helped to discover a variety of unexpected effects produced by a long lasting giant "storm" of interplanetary dust particles, captured as "juvenile" micrometeorites by the young Earth. It produced a fantastic long-duration storm of shooting stars, with an hourly rate of about 10 million (and not about 10 like today), and which lasted for about 100 Myr after the formation of the Moon.

As about 75% of the incoming flux of micrometeorites is destroyed upon atmospheric entry, either by volatilization or melting, this silent cosmic dust storm effective in the thermosphere (i.e., between about 120 km and 80 km today) induced a new kind of diffuse and soft volcanism "falling from the sky". It thus injected in particular strong greenhouse gases (H_2O, SO_2 and CO_2) and very small "smoke" particles in a kind of giant ∼50 km thick "cocoon", located in the thermosphere, and which did homogeneously cap the whole early Earth's surface for a duration of about 100 Myr!

This accretion was mostly effective just after the formation of the Moon by the impact of a giant Mars-sized body with the Earth. This cataclysmic impact simultaneously blew off most of the complex pre-lunar terrestrial atmosphere, thus leaving a vacant "niche" for the subsequent accumulation of a post-lunar mixture of volatile species generated by this long duration micrometeoritic volcanism. It ended up forming the air and oceans of the early Earth. Furthermore, altogether with micrometeorites that do survive unmelted upon atmospheric entry, it likely opened many new reaction channels that contributed dominantly to the prebiotic chemistry that gave birth to life on the Earth, and possibly on Mars and a few planets orbiting around other Sun-like stars.

One of the key findings supporting this scenario is the astonishing chemical "purity" of the $\sim 2.10^{24}$ g of volatiles that compose the Earth's atmosphere formed ∼4.4 Gyr ago, and which includes the air and oceans, but also sedimentary rocks such as the ∼270 millions of km^3 of carbonates where early CO_2 is now trapped. Indeed, this mixture of volatiles is similar to that expected for a tiny "puff" of gases, which would be released upon the frictional heating of ∼5 mg aliquot of ∼500 micrometeorites with sizes of ∼100–200 μm, and similar to those recovered from recent Antarctic ices –this is the number of Antarctica micrometeorites, which were painstakingly analyzed over the last decade to determine their average Ne, N_2, H_2O and C contents. We further strengthened this deduction while showing that previous scenarios used to tackle the same problem, as well as interesting criticisms addressed to our model, all roughly stumble against this micrometeoric purity that they can hardly bypass.

Next, we decided to further check the validity of this scenario switching to the concentration of a very refractory and highly siderophile element (iridium) in the very different environment of the Earth's mantle. The good fit between predictions and observations for rocks from the upper mantle did build up our confidence to explore the unexpected potential of micrometeorites to decrypt other mysteries of our distant past.

The readers of this book will be in touch with very recent ideas about our origins, which are either still hotly debated or even not published yet – if they want to have a conventional view of the topics discussed in this book they have just to turn to the beautiful Encyclopedia available today. Therefore, the first chapter is a kind of teaching help where they will find the basics required to understand these ideas and the importance of the data that support them. Moreover, these basics will be further developed in each of the following chapters. For example, the complex classification of meteorites, which has already been presented in detail in excellent monographs, will be summarized in just four pages, trying to keep only the most salient features of this classification (Sect. 6.1). Modern ideas about the origin of life, which have also been presented in good monographs, are sketched in the two and a half pages of Sect. 12.1. We also selected a set of 52 figures, which might be consulted first to get a feeling about the topics discussed in this book.

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I benefited from the long-term support of a few colleagues and institutions. They include:

- Robert M. ("Bob") Walker, for his requiring teaching about "good research" when I was his first PhD student and favorite teacher about french wines;
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- the glaciologists Claus Hammer and Michel Pourchet, who ensured the success of all our expeditions in Greenland and our two first expeditions in Antarctica, respectively;
- the mineralogists Gero Kurat and Mireille Michel-Levy, who spotted first many interesting characteristics of micrometeorites, including their dominant relationship with CM-type chondrites;
- André Brack, who constantly supported our intrusions in exobiology;
- Jacques Reisse, for a decisive stimulating review of our first paper about the formation of the Earth's atmosphere;
- the radioastronomer Jean-Louis Steinberg, who strongly endorsed our first proposal to collect micrometeorites in Greenland, which paved the way for the funding of our 10 subsequent expeditions in Greenland and Antarctica, between 1984 and 2002;

- Christian Jouret and Patrick Veyssières, who initiated the decrypting of the fossil record of micrometeorites on a microscale by analytical electron microscopy;
- Philippe Bonny, who did a still unsurpassed modeling of the atmospheric entry of micrometeorites and ended up composing electronic music;
- George Slodzian, who conceived one of the most powerful instruments of our discipline, the ion microprobe (and its latest version, the NanoSIMS), which has opened so many fruitful areas of research;
- The two truly multidisciplinary scientists, who did a very constructive review of a preliminary version of this book, submitted on a great date in the French folklore (i.e., April 1st 2004);
- the French institutions IN2P3 and CNES, from which we received most of our funding, and IPEV, which supported our five splendid summer vacations (i.e., from December to February) in Antarctica, in the company of steam generators.

The most difficult thing when you are right is to prove that you are not wrong

Pierre Dac
French humorist
1893–1975

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Part I

Staging the Cosmic Theater

This first part is a kind of teaching help. We briefly present solar system bodies and discuss the "power" of Jupiter. Next, we outline modern scenarios dealing with the formation of the Earth and the Moon as to better sketch the cataclysmic period of the "late heavy bombardment" of the Earth–Moon system, and some of its major effects. This background already allows us to identify a plausible suspect for the formation of the $\sim 2.10^{24}$ *g of the Earth's atmosphere, back about 4.4 Gyr ago. This is a giant long-duration storm of tiny cosmic dust grains called micrometeorites in this book.*

1 Solar System Bodies and "Primitiveness"

***Planets and small bodies*.** Besides the Sun, which represents about 99.85% of its mass, the present day solar system include large bodies, i.e., the four terrestrial planets, the four giant planets, and Pluto, which is probably not a planet, but rather an object from the Edgeworth–Kuiper belt of comets captured by Neptune; more than 130 satellites of the planets. Jupiter, the most massive planet of the solar system, is about 320 times more massive than the Earth, which weighs about 80 lunar masses. Its orbit separates the two very distinct worlds of the inner solar system, populated by rocky bodies, from the outer solar system, which is the world of the giant gaseous planets, icy bodies and intense coldness, which starts at around 5 astronomical units (AU) from the Sun and ends up at 50,000 AU with the outer edge of the Oort cloud of comets –one AU is the average distance between the Earth and the Sun, of about 150 millions of km.

Moreover, there is a myriad of much smaller objects that constitute the vast family of the "small bodies". The largest ones include rocky bodies called asteroids, and comets composed of dirty ices containing about $\leq$50 wt% of dust grains. The sizes of comets observed at the Earth's orbit as yet are typically $\sim$10 km, while the largest asteroid, Ceres, is about the size of Texas. Comets and asteroids are the "parent bodies" of interplanetary dust particles temporarily trapped in the faint zodiacal cloud. The current total mass of the small bodies is about 0.015% of the mass of the Sun. The mass of the zodiacal could (about 2×10^{19} g) corresponds to that of a $\sim$10 km size asteroid.

***Present-day configuration of asteroids*.** Britt and Lebofsky (1999) gave a well-illustrated discussion of the science of asteroids, which include a good discussion of the relationships between asteroids and meteorites. Their Fig. 1 clearly illustrates that the 7722 asteroids with the best-determined orbits (and sizes $\geq$20 km) are mostly found in the main asteroidal belt that extends from about 1.8 to 4 AU, and which is very flat (i.e., that the inclination of their orbits on the ecliptic plane is smaller than 10°). The full inventory of asteroids with sizes $\geq$20 km has been made (about 50,000 objects) and one expects about 500,000 asteroids with sizes $\geq$1 km.

There are much more smaller than large asteroids. The total current mass of the asteroidal belt represents about 4% of the mass of the Moon, and about half the mass of micrometeorites accreted by the Earth since the formation

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of the Moon. Ceres, the largest asteroid (size about 940 km), represents half the mass of the asteroidal belt.

Asteroids with sizes ≤ 300 km would have been fragmented during energetic interasteroidal collisions. Some fragments may have been re-accreted as to build-up new asteroids made of loosely gravitationally bound "rubble piles". However, the 7 largest asteroids with a size $\geq$300 km would be the remnant of the initial population of asteroids.

Present-day configuration of comets. Today, the more than 10^{12}–10^{13} comets mostly populate two major distinct reservoirs:

- the inner margin of the Edgeworth–Kuiper belt (EdK belt) mostly extends from the orbit of Neptune (about 30 AU) to a sharp boundary at $\sim$50 AU. It contains about 0.1 Earth's mass. But its outer margin would spread to probably several hundred AU. It is quite flat like the asteroidal belt and might contain several tens of Earth masses, and;
- the more distant Oort cloud with a spherical shape, spreading up to about 50,000 AU, and that would contain about 30–40 Earth masses.

These two reservoirs are the sources of three classes of comets, which can reach the inner solar system as to generate interplanetary dust particles upon the volatilization of their dirty ices. They include:

- The long period comets with orbital periods, P, larger than 200 years. Therefore, they have only been observed once, and one does not know whether they are periodic or not. Their orbits have random inclinations on the ecliptic plane. They were expelled from the outer margin of the Oort clouds by various gravitational interactions rooted in the motion of the solar system in the galaxy (i.e., those induced by passing nearby stars and massive interstellar clouds). They represent about 80% of the comets among the thousands of comets that have well re-reconstructed orbits:
- The short period *Halley-type* comets (20 years $\leq P \leq$ 200 years) have random inclinations like long period comets. They have been observed at least twice, and they represent about 2% of the comets. They are probably Oort cloud comets captured into the inner solar system by gravitational interactions with the planets;
- The short period Jupiter family comets ($P \leq$ 20 years), have inclination close to the ecliptic plane ($\leq 40°$). They would have been extracted from the inner margin of the EdK belt (i.e., at heliocentric distance of 30–50 AU by the gravitational interactions of the giant planets. They represent about 18% of the comets reaching the inner solar system.

Beware of the elusive early history of comets. The science of comets involve many disciplines. It looks easy to focus on the study of the rare comets that visit the inner solar system where they become visible as a result of the sublimation of their ices at heliocentric distance $\leq$2.5 AU. This triggers the formation of their beautiful tails that might be very long, extending up to

10^8 km. Most of the time, astronomers can even reconstruct their orbits back to the original reservoirs from which they were extracted. But as soon as you want to reconstruct the early history of comets during the first 500 Myr history of the Earth, you start piling up questions, which have been answered in very different ways.

For example, let us take the important measurement of the D/H ratio in the tails of comets. The measurements have only been made on 3 comets from the Oort cloud. Would comets in the other reservoirs yield the same ratio? Are we sure that the ratio measured in the gases of the tails gives the ratio initially locked in the ices? Therefore, what was the actual primordial D/H ratio of cometary ices, which is a very important tracers of the history of cometary ices? Is it really different from that of the dust grains trapped in the ices?

Next, let us switch to planetary dynamics, and go back in time to wonder about the origin of comets. Suddenly, you realize that most efforts to go backward in time use the simple but unrealistic assumption that the distribution of solar system bodies in these earlier times was the same as today. Then, reading the interesting paper of Levinson et al. (2001) that focuses on the origin of the "spike" of impactors that formed the large lunar impact basins back to 3.9 Gyr ago (see below), you suddenly realize that a delayed growth of Uranus and Neptune would have drastically destabilized not only the orbits of the small bodies (comets and asteroids) but also that of Jupiter. In particular, Jupiter was moving slightly inward. These bursts of migration triggered a cascade of phenomena, such as severe shifts of the position of various types of orbital resonances (see below) that allow extracting asteroids and comets from their reservoirs as to fire them to the Earth.

The formation of Uranus and Neptune is still considered one of the major outstanding problems in planetary science. So, how do you want to trace back the history of the "extraction" of comets from their major reservoirs as long as you do not understand this problem?

Then trying to go further back in time you hit another major problem. The Sun was born in a stellar nursery. What was the number of stars in this nursery? This is an important information because its rules the half-lives of stars in the nursery that can gravitationally perturb the outer margin of the Oort cloud of comets, as to fire them to the inner solar system. Therefore, an essential part of the early history of comets might be locked in the mystery of this nursery.

These difficult problems can hardly be discussed in the framework of conventional reviews, probably because their discussions might seem too speculative. At least, I was completely free in this book to navigate out of sight in this dangerous territory in space and time where science merges with science fiction. This ended up increasing the impressive pile of questions, and shaking up conventional wisdom.

Small bodies are also Parent bodies. These comets and asteroids are the parent bodies of much smaller innumerable debris with sizes that peak around 200 μm, and extend up to a few meters (see Sect. 7). The Earth can capture such debris as meteorites and micrometeorites, after their flight times in the interplanetary medium since their ejection from their parent bodies. These flights last for about a few 100,000 yr and a few to about 70 Myr for micrometeorites and stony meteorites, respectively (see Sect. 22.3).

The size limit of a few meters for a rather "intact" capture of an extraterrestrial body by the Earth reflects the aerodynamical braking of these objects in the present day atmosphere during their collisions with air molecules. The contemporary atmosphere is equivalent to a ∼10 meters thick layer of water around the Earth. An impacting body will be decelerated to free fall velocity when it will have swept its own mass of air and this corresponds to a mass smaller than about 10 tons. Consequently, most micrometeorites with a small size of around 100–200 μm will typically decelerate between ∼120–80 km of elevation, in a specific layer of the atmosphere called the thermosphere. However, larger meteorites, which are mostly hand to fist sized, have to penetrate deeper in the atmosphere and they typically slow down between ∼80–20 km.

When their sizes exceed a few meters (i.e., a mass of ∼100 tons) these bodies cannot decelerate –except if they follow a shallow incidence– and they explode while hitting the Earth's surface, producing explosion craters. The crater diameter and its "instantaneous" depth are about 10–20 times and 2–3 times larger than the size of the impactor, respectively. But the depth decreases quickly because the compressed crater floor is quickly uplifted. As their very high speeds range from about 11 to 70 km per second, they have an impressive explosive power. For example, an approximately 10 km size body with a speed of 20 km/s would explode like about 5 billion atomic bombs of the Hiroshima type. The explosion is best simulated by the chemical explosion of TNT, not by the much shorter nuclear explosion of an atomic bomb.

Primitiveness of meteorites and asteroids. Fish, Cole and Anders (1960) revolutionized the science of meteorites ("Meteoritics") about 45 years ago. Before their work, it was thought that the various classes of meteorites originated from a small planet, which was disaggregated upon impact. This planet supposedly formed by the accretion of primitive material formed in the early solar system. However, this material melted while losing its "primitiveness", and the planet developed an "onion" type layered structure rather similar to that of the Earth, and including:

- a core made of an alloy of nickel and iron (FeNi) that yielded the iron meteorites containing tiny and rare stony inclusions;
- the boundary between the core and the upper layer (e.g., the "mantle") was the source of the stony-iron meteorites, made of a mixture of much larger silicate inclusions and FeNi;
- the mantle and its top "crust" were the parent reservoirs of the stony meteorites, divided into chondrites and achondrites depending whether or

not they contain chondrules, which are typical rounded once-melted objects not found in terrestrial rocks.

The work of Fish et al. (1960) fiercely collided with this paradigm. They reported evidences indicating that meteorites originated from a huge diversity of bodies trapped in the asteroidal belt. Most of them were too small as to be strongly heated during formation, and thus kept their "primitiveness" –heating results from the accretional energy deposited during the impacts of the bodies merging into an asteroid and radioactive decay, which were both much more intense than to day. This challenging deduction was verified many times since this pioneering work. It rejuvenated completely the field of Meteoritics, which became a very active discipline. About 300 groups worldwide are working on these cosmic stones today.

Thus, with the exception of lunar and Martian meteorites, most of these objects are much older than terrestrial and lunar rocks. This "primitiveness" represents their major interest. Most of them are made of constituent grains formed at about the same time as the early Sun, in a collapsing fragment of interstellar cloud of gas and dust, called the solar nebula. In this cloud most of the original interstellar grains were destroyed upon volatilization and/or deeply altered when the Sun was formed. Together with those resulting from the condensation of hot nebular gases they are dubbed as *being formed* in the solar nebula. This mixture of grains was subsequently incorporated into small bodies such as comets and asteroids where they have been stored for billions of years.

Large asteroids and/or smaller ones resulting from their subsequent fragmentation upon collisions might have melted soon after their formation because their surface-to-volume ratio was too small to allow for an efficient cooling during formation. Thus, telescopic remote sensing of mineralogical composition shows that the surface of the second largest asteroid, Vesta, with a size of 525 km, is clearly made of basalts resulting from the cooling of magma. However, to complicate this issue, the same remote sensing show that the surface of the largest asteroid, Ceres, with a size of 940 km, would be made of a dark material considered being rather similar to the CI-type and CM-type primitive meteorites. It this case it is unlikely that Ceres was ever melted.

The primitiveness of meteorites is more appropriately discussed in Sect. 6.2 and 25. This is a kind of fuzzy characteristic. For example, a very efficient process of hydrous alteration did drastically alter the mineralogical composition of CI-type chondrites. However, this process was effective in a closed chemical system. Therefore, it did not modify their bulk chemical composition, which is considered to be the most primitive one (i.e., the nearest to the composition of the solar atmosphere). For this important group of rare meteorites (0.5% of the meteorite falls), primitiveness includes the chemical composition but excludes the mineralogical composition!

A biased selection of asteroidal meteorites? Meteorites are considered to originate from interasteroidal collisions. Therefore, numerous similarities should be expected between meteorite and asteroid families. One of the most powerful techniques to analyze asteroids is to look somewhat at their "color" using visible and near-infrared reflectance spectroscopy conducted with ground-based and Earth-orbiting telescopes. These observations also yield precious clues about their mineralogical composition. They constitute a kind of fingerprinting, which can then be compared to those obtained for meteorites in the laboratory.

One of the most intriguing problem of Meteoritics is that very few (i.e., none ?) asteroids give spectra that match those of meteorites –c.f., the review of Britt and Lebofsky (1999) in Sect. 3 of their paper. For example, let us take two examples that are relevant to our works;

- the ordinary chondrites that represent about 80% of the meteorite falls (see Sect. 6.1) would be only similar to the dry S type asteroids that dominate the inner margin of the asteroidal belt between about 2–2.6 AU. However, the spectra of these asteroids have a strong red slope never observed in the ordinary chondrites;
- Antarctic micrometeorites are only related to the relatively rare group of the CI- and CM-type hydrous-carbonaceous chondrites that represent about 2.5% of the meteorite falls (see Sect. 6.3). These chondrites would best correspond to the C-type asteroid, dominantly found between about 2.6 and 3.5 AU. However, the spectra of these C asteroids are now less red than that of these meteorites.

Besides the ill-defined effects of "space weathering" that might masquerade the pristine colors of asteroids, planetary dynamicists suggested that several processes biased the extraction of meteorites from the belt. They involve kinds of deep well in the distribution of the number of asteroids as a function of their semimajor axis (i.e., their "average" distance to the Sun), in which the orbits of meteorites and asteroids get unstable –c.f., Britt and Lebofsky (1999), Fig. 4. These instabilities result from different types of gravitational effects that Jupiter can exert on nearby bodies.

The "simplest" one produces *Mean Motion Resonances* (MMRs), which are activated when the orbital period of an asteroid is a simple fraction of Jupiter's period (11.86 years), such as 1/3, 2/5, etc. In many cases MMRs lead to chaotic motion, driving a body into a planet crossing orbit. In this case a close encounter with the terrestrial planets or Jupiter might end up as collision with a planet or an ejection of the solar system. There are also other types of "secular" resonances, such as the famous γ_6 resonance, which is related to "*precession rates of the longitudes of perihelion*" and the ν_{16} resonance *for "orbits with librating arguments of perihelian"* –as I could hardly memorize the right positions of the 7 words in these quotations, secular resonances will not be further discussed in this book. Just remember that they can also lead to chaotic motion and collisions.

These computations suggest that most meteorites (as well as planet-crossing asteroids) might only originate from the 1:3 MMR and the γ_6 resonances that are both located in the inner margin of the EdK belt (i.e., from about 2 to 2.6 AU). In this zone, the population of asteroids is dominated by dry materials, which were once melted and/or subjected to a strong heat metamorphism. In this case, meteorites represent a biased sampling of asteroids. In Sect. 27 we extend this discussion of the folkloric world of biased samplings to micrometeorites.

Primitiveness of cometary dust grains. Before the first appearance of the Hale–Bopp comet in the inner solar system in 1995, it was generally thought that comets were made of the most primitive material in the solar system. Their dust component would just be unprocessed interstellar material (Delsemme, 1998). This view is questionable. It is very likely, as first suggested by McSween and Hapke (1989) –their paper was ignored until recently– that cometary dust grains were first reprocessed in the solar nebula before being incorporated into cometary ices (see Sect. 24).

The recent work of Shu et al. (2000) suggests that they rather formed in the inner solar system in the first place, and then got subsequently transported to the distant cold formation zone of cometary ices by huge surges of nebular gases, functioning as kinds of gigantic dust belt conveyors, such as the "x-wind" of Shu (c.f., Sect. 24.1). Therefore, cometary dust grains would not be as primitive as previously thought. In particular they should contain refractory phases such as anhydrous crystalline silicates and calcium-aluminum-rich refractory inclusions (CAIs), which can only be formed at high temperature near the Sun. On a scale of primitiveness, they would just rank on a par with the constituent material of the most "primitive" meteorites, the hydrous-carbonaceous chondrites, which are loaded with volatile species (see second rubric in Sect. 24.1).

Moreover, to further confuse the difference between comets and asteroids it cannot be excluded that the CI- and CM-type hydrous–carbonaceous chondrites to which 99% of the Antarctic micrometeorites are related could either originate from dormant comets trapped in the asteroidal belt or were lifted off as rocks from the surface of small active comets with sizes ≤ 5 km (Lodders and Osborne 1999; Napier 2001).

Gounelle et al. (2005) did even reconstruct the orbit of the most famous of the CI-type chondrite, Orgueil, from the past historic record, when farmers witnessed its fall in the France on May 14^{th}, 1864. They quoted that they saw a "*falling full Moon*"! With the help of the farmers, Gounelle et al. argued convincingly that the aphelion of Orgueil exceeded 5.2 AU. In this case, the meteorite would be a rock from a Jupiter family comet.

2 The Power of Wetherill's Friend, Jupiter

Jupiter is a gigantic gravitational sling that can alter the orbits of small bodies while triggering their "chaotic" diffusion. This property was used to fly the spacecraft Ulysses around the solar poles. Ulysses was not fired directly to the Sun but to Jupiter, which did sling it back to the Sun, thus saving the spacecraft a lot of energy.

The absence of a small planet between Jupiter and Mars is now attributed to the gravitational power of Jupiter, which prevented the completion of the first stage of accretion of asteroids into a small planet. Subsequently, interasteroidal collisions could throw primitive debris in the interplanetary medium, including meteorites and micrometeorites. In this case, Jupiter would be responsible for the delivery of primitive asteroidal meteorites and micrometeorites to the Earth that now allows us to decrypt the early history of the solar system, including that of... Jupiter!

About comets, a straightforward view is to assume that they were likely formed in the most inner zone of the outer solar system where the density of matter to feed their growth did reach the highest value. Jupiter was playing a bewildering role in the diffusion of the orbits of this initial "primeval" population of comets. Most of them were ejected from the solar system, but a small fraction were thrown into the two major secondary reservoirs from which they mostly originate to day, the EdK belt and the Oort cloud that are considered as the sources of the periodic and non periodic comets, respectively.

To release cometary material in the inner solar system and/or to decimate the dinosaurs upon a direct hit with the Earth, the orbits of the comets trapped in these two distant reservoirs have to be perturbed first as to fall in the zone of gravitational influence of Jupiter. These "preliminary" perturbations involve:

- Uranus and Neptune for the EdK belt comets, and;
- nearby passing stars and interstellar clouds, for comets from the outer margin of the Oort cloud. When they reach the sphere of gravitational influence of Jupiter they can be fired to the inner solar system as to generate interplanetary dust particles (and even rocks) during the sublimation of their dirty ices at heliocentric distances ≤ 2.5 AU, which will be subsequently captured by the Earth as micrometeorites.

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In brief, it is likely that without the gravitational power of Jupiter, primitive interplanetary debris from either asteroidal or cometary bodies would not have been captured by the Earth in large and thus recoverable quantities, as to be exploited in this book as key fossil archives of our distant past. Possibly more important Wetherill (1995) coined Jupiter as "our friendly Jove". He noted that without a large planet positioned precisely where Jupiter is, the Earth would have been struck a thousand times more frequently in the past by comets, meteors and other interplanetary debris. Consequently, there would be no life form thriving into it, as to write all kinds of science fiction books.

3 The Earth–Moon System in a Gigantic Cosmic "Firing" Range

Many observations remind us that the Earth–Moon system has been bombarded by projectiles covering a wide size range between submicrometer particles to the giant Mars-sized body that did form the Moon during its impact with the proto-Earth. They include:

- shooting stars observed in the Earth's atmosphere;
- the surface of cm-sized lunar glass beads that are riddled with microscopic impact "pits";
- the 88 large lunar impact craters with diameters ≥100 km observed on the near-side of the Moon;
- the ∼170 large impact craters with diameters ranging from a few tens of m to ∼300 km identified on the Earth's surface (with a few new candidates being found each year). Moreover, the sharp increase with age of the density of impact craters with sizes ≥4 km on the Moon (number per unit time and unit area) revealed that the flux of these objects was much higher prior to around 3.5 Gyr. This section briefly outline major effects of this early and/or late heavy bombardment of the Earth that are frequently used in this book, and which led us to suspect that a gigantic storm of juvenile micrometeorites was mostly responsible for the formation of the Earth's atmosphere.

3.1 The Artistry of Radiochronometers

In this book we use two time scales. In the conventional one, the origin of time is today, and the formation of the solar system occurred back to 4.566 Gyr ± 0.002 Gyr ago, when the solar nebula were isolated in the galaxy, and were thus shielded from the admixture of freshly synthesized radioactive nuclides and/or interstellar dust grains. The value of 4.56 Gyr is assimilated to the ^{207}Pb$-^{206}$Pb radiometric "model" age of two Calcium–Aluminum-rich refractory inclusions (CAIs) of the Efremovka CV3-type carbonaceous chondrite (Amelin et al., 2002), which are considered to be the first mineral phases to have condensed quickly during the cooling of the solar nebula.

The functioning of this powerful radiochronometer is difficult to explain. It is based on the measurements (with a mass spectrometer) of the concentra-

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tions of both the products of the radioactive decay of two uranium isotopes (^{235}U and ^{238}U) in ^{207}Pb and ^{206}Pb, respectively, and the stable ^{204}Pb isotope that is used as the "reference" nuclide. Then, the knowledge of the mean lives of the two uranium radioactive isotopes (they scale their average rate of radioactive decay) would give the "age" of the CAIs, i.e., the time interval between the isolation of the solar nebula in the galaxy that stopped the admixture of uranium and lead isotopes, and the crystallization of the CAIs.

Geochemists have developed a panoply of other radiochronometers (see Sect. 29.3). In all chronometers the parent and daughter nuclides are not made of the same chemical element. The parent nuclide was generally quite welcomed in the lattice structure of its host minerals. However, the daughter nuclide is just an intruder ready to get partially expelled during subsequent episodes of thermal metamorphism, shock, weathering, etc. In this case the chemical system in which the parent and the daughter nuclides were trapped was not closed and this prevents the definition of a meaningful "model" age. Therefore, the science of radiochronometry is difficult and has to be handled by geochemists, who also have top expertise in mineralogy and petrography (these two fields combine to yield the artistry of reconstituting the history of a rock subsequent to its formation).

We also refer to a kind of nebular calendar to zoom in on early solar system processes, which mostly occurred in a narrow time interval of about 100 Myr after the isolation of the solar nebula. Here, the art of radiochronometry becomes even trickier as it handles "extinct" radionuclides with short mean lives that range from about 1 Myr (^{26}Al, ^{36}Cl and ^{41}Ca) to 150 Myr (^{149}Sm). Therefore, they do not exist any longer today and to play seriously with them, you have to be an expert in geochemistry, mineralogy, petrography and nucleosynthesis. Now, time "zero" corresponds to the isolation of the solar nebula and today is about 4.56 Gyr older. On this nebular time scale, the formation time interval of the Earth, $\Delta\ (Earth) \sim 100\,\mathrm{Myr}$, will be the basic time frame of our scenario.

3.2 Formation of the Moon by the Last Planetary Embryo Merging the Earth

Accretion of planetary embryos in about 100 Myr. The young Earth started to retain an atmosphere when its mass reached around 5% of its final value. If the Earth did not have a Moon, its atmosphere would be very complex.

Indeed, in modern scenarios of the formation of the terrestrial planets pioneered by Wetherill (1994), the formation of the Earth involves two major stages –c.f., Cassen and Woolum (1999) for a general concise introduction (with only 6 references!), and Canup and Agnor (2000) and Genda and Abe (2003) for a more technical discussion of previous works. They include: (**i**) a runaway accretion of small bodies about 10 km size in (i.e., "planetesimals"). This very short stage (≤1 Myr) led to a proto-Earth with a mass of about 16 lunar masses (i.e., two Martian masses). Simultaneously, the same processes formed about tens to hundreds of planetary embryos (with masses of 1 to 10 lunar masses) in the whole inner system; (**ii**) the second and longest stage of accretion, which led to the terrestrial planets, was carried out by the collisions and mergers of these planetary embryos.

In the case of the Earth, the duration of this second stage, which involved the accretion of about 6–10 embryos, was estimated to be ∼100 Myr. It defines the formation time of the Earth, Δ (*Earth*) ∼ 100 Myr, that was closed after the merging of the last planetary embryo. Canup and Agnor (2000) investigated the fate of the swarm of large embryos with a high relative angular momentum capable of forming a Moon around a terrestrial planet. The results of their numerical simulation (see their Fig. 8), clearly show that this reservoir was somewhat abruptly emptied around the end of Δ (*Earth*). In fact, they write, "*high angular momentum collisions continue to occur until about 100 Myr when the final planets are well separated and accretion is nearly complete*".

Moreover, concerning the impact of the latest embryo, about 50% of the *latest are also the largest* and the remaining 50% would be the *second largest ones*. Later on, Canup and Asphaug (2001) did convincingly argue that after this last embryo merger, the Earth did reach about 99% of its final mass (i.e., its formation time interval was essentially closed). Moreover, the material ejected in space during this cataclysmic impact did form the only large Moon of the inner solar system. During all this period of cataclysmic impacts by planetary embryos the surface of the Earth was probably molten by the energy of accretion and envisioned as a gigantic "magma ocean" extending to a depth of about 1000 km.

This theoretical estimate of Δ (*Earth*) ∼ 100 Myr is comforted by measurements of ages inferred from radiochronometers. A first value was inferred from the ^{129}I–^{129}Xe radiochronometer (Pepin and Phinney 1975; Staudacher and Allègre 1982). The validity of this chronometer was thoroughly checked recently while comparing the I–Xe age of various mineral phases of chondrules of the Richardton H5 chondrite with the lead radiometric ages of the same chondrules (Pravdivtesa et al., 2002). Within a systematic difference of about 2–3 Myr these ages are remarkably similar.

A second estimate can be deduced from the age of the lunar crust (4440 ± 20 Myr) which was reported by Carlson and Lugmair (1988) for the Apollo 16 anorthosite 60025, and which did form very quickly after the Moon forming impact. It thus signals the end of Δ (*Earth*) ∼ (4.56 Gyr–4.44 Gyr) ∼ 120 Myr. Then, the terrestrial oceanic crust was formed at the latest around 4.4 Gyr ago –this value was deduced from the dating of old detrital zircons (see, Sect. 23.5, 5$^{\text{th}}$ Subsect.). Therefore, we selected a value of $\Delta Earth$ ∼ 100 Myr, even though it looks challenged by the shorter value of about 34 Myr deduced from the new Hf–W radiochronometer (Schoenberg et al., 2002). However, this chronometer gives "model" ages that are still not fully understood (c.f., Sect. 29.3).

3.3 From Highly Cratered Highlands to Sparsely Cratered Mare on the Moon

As soon as the lunar crust was formed it started to behave as a gigantic detector of impacts which did play a decisive role in our research, as it allowed estimating the amplification of the micrometeorite mass flux in earlier times relatively to the present day value. The exploitation of this fossil impact record is more appropriately discussed in Sect. 23. The discussion presented in this section is mostly based on the works of Hartmann (1999, 2002), Ross (1999), Hartmann et al. (2000), Levinson et al. (2001) and Greaves (2005).

A unique record of the "late heavy bombardment" on the Moon. The Earth is accompanied by a Moon where the astronauts have recovered around 382 kg of soil samples and rock fragments from six landing sites. A major difference with the Earth is the lack of plate tectonics, which could have recycled the early lunar crust, formed about 4.44 Gyr ago. Therefore, this crust is still preserved in the highly cratered bright lunar highlands. They are made of a megaregolith composed of feldspathic rocks lighter than the underlying basalts of the lunar mantle on which they initially "floated" when the Moon was partially melted. These rocks were heavily fragmented, turned over and sometime remelted up to a depth of around 20 km, during the intense bombardment of the lunar crust. This depth defines the thickness of the porous heavily fractured layer coined as the megaregolith. This thickness corresponds to a discontinuity in the propagation of "P-seismic" waves, indicating a sharp closure of porosity at that depth –all these details are more appropriately discussed in Sect. 21.1.

About 600 Myr later, a "spike" of large impactors, presenting a maximum in intensity around 3.9 Gyr ago, and which lasted for about 150 Myr, formed the 12 large impact basins on the front-side of the Moon with diameter ranging from 300 km up to 1300 km –the timing and duration of this spike were directly inferred from the distribution of the formation "ages" of lunar breccias. Later on, the basins just acted as depressions that were flooded by basaltic flows originating from magmatic chambers seated at depths of about 300–400 km in the lunar mantle, and which are not related directly to the spike of impactors (Ross, 1999). After solidification, these basalts formed the dark mares that are sparsely cratered, because the flux of impactors had declined to a much lower value. For this reason, they could only develop a thin mare regolith with an average thickness of about 4–5 m, during the impact comminution of these basalts –see next section.

Variation of lunar cratering rates with time. The radiometric dating of the rare igneous rocks collected by the Apollo astronauts yielded that of their parent surfaces, which might be quite far away from the collecting site, in the case of a rock deposited along a bright crater ray. High-resolution pictures were used to make an accurate counting of impact craters with diameters $\geq$4 km on these parent zones. This study revealed that old lunar highlands are much more heavily cratered than the younger dark mare, and this important difference can be observed with a simple binocular.

This is reflected by the variation with time of the relative lunar cratering rate, $K(t)$ (e.g., the number of craters formed per unit area and unit time, *relatively to the present day value*), which has been measured up to around 3.9 Gyr ago. Beyond this date the measurements cannot be done because the old surfaces get saturated with impact craters and because the oldest rocks were destroyed by high impact rates. Also, still older rocks may be present, just unsampled. The values of $K(t)$ have to be extrapolated with models to the time of formation of the Moon by a giant impact with the Earth. We selected the extrapolation conjectured by Hartmann (1999), which corresponds to a fast and smooth roughly exponential increase of $K(t)$ when going backward in time (Fig. 1) –see Sects. 10.5 and 23.3 for a justification of this conjuncture.

This curve delineates the period of the *late heavy bombardment* of the Earth/Moon system (LHBomb). It shows that during the time interval of about 100 Myr that followed the end of $\Delta(Earth) \approx 100$ Myr, and that will be coined as the “peak” of the post-lunar LHBomb, this cratering rate was on the average about 10^6 times higher than today! In this conjuncture, the initial value of the relative impact rate back to about 4.6 Gyr ago ($\sim$2.10^9) corresponds to the value necessary to accrete one Earth’s mass in about 50–100 Myr.

This curve will be one of the two key tools, which will allow the computation of the integrated micrometeorite mass flux accreted by the Earth at any time, t, after the formation of the Moon (see Sect. 10.4). Moreover, the slope of this curve (that looks like a radioactive decay curve) defines the half-life, $t_{1/2}$, of the population of impactors –i.e., the amount of time required to decrease by a factor 2 the number of bodies, in population of objects as different as radioactive nuclei and comets, which roughly exponentially decays with time. It will give a hint that these early impactors were dominated by comets (see Sect. 23). In these units of time the mean life used in Sect. 3.1 is just $1.44 \times t_{1/2}$.

There are other conjunctures to describe the period of heavy bombardment, which probably all derive from *the lunar terminal cataclysm* initially proposed about 30 years ago by Tera et al. (1974). This conjuncture, which is still quoted today, would correspond to an intense burst of impactors centred around 3.9 Gyr ago. It was initially thought that this spike was the only major burst of impactors that affected the lunar crust. It thus col-

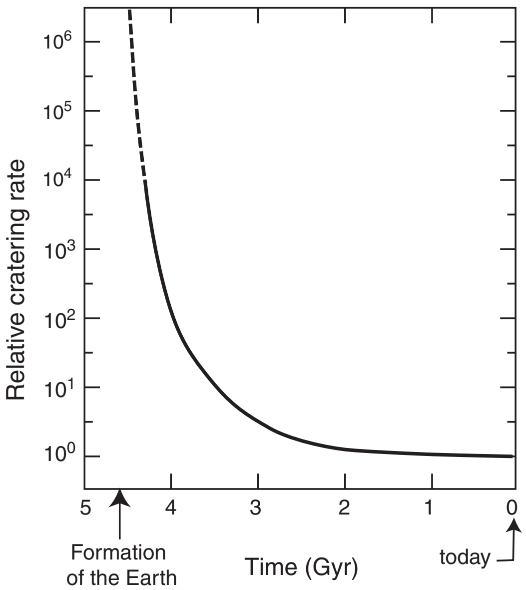

Fig. 1. Variation with times of relative lunar cratering rate, $K(t)$. This roughly exponentially decaying curve reflects the conjuncture of the early heavy bombardment proposed by Hartmann –it will be rather coined as late in this book (LHBomb) as to encompass other conjunctures. Such rates refer to the number of impact craters with sizes ≥ 4 km, per unit time and unit area, relative to the present day value. Beyond 3.9 Gyr ago, they cannot be measured and have to be conjectured with a model (Courtesy of W. Hartmann).

lided with the conjuncture of Hartmann, which postulates a roughly exponential decline of the flux of impactors since the formation of the lunar crust. Nowadays, most scientists agree that this cataclysm is not a substitute for the LHBomb. It just spiked the exponential decline of $K(t)$ with a total mass of impactors that was smaller than that delivered by the LHBomb since the formation of the lunar crust. Moreover, the peak in this distribution is not clearly understood –see Sect. 23.4.

A "debris disk" to feed the LHBomb? During its evolution to the main sequence a young Sun-like star is surrounded by a disk shaped parent nebula that lasts for about 1–10 Myr. Since 2001, astronomers investigating the thermal emission of dust around stars with IR telescopes got progressively convinced that a high proportion of stars (about 45%) are "debris disk" stars (DD-stars), where dust would have been continuously regenerated by the collisions of planetesimals after the clearing of the early stellar nebula (see the stimulating paper of Greases, 2005). It was first thought that such disks could hardly survive beyond a few 100 Myr. But it has been recently found that they can persist for much of the lifetime of the stars. Therefore, a Sun like star with a short-lived DD might represent a minor fraction of the stars (∼15%).

Greaves even suggested that the DD-phase of the young Sun “*might be analogous to Earth's early period with a high-impact rate called the heavy bombardment*”. However, after the formation of the Moon the rocky planetesimals formed in the inner solar system were essentially locked in the planetary embryos, which merged as to make the terrestrial planets and, possibly, the rocky cores of the giant planets –i.e., a total mass of material of about 50 Earth mass. Therefore, the planetesimals still present during the post-lunar period in the large volume of the solar DD (they have radius ranging from about 50 to 500 AU) were essentially comets formal in the outer solar system, and that we still observe to day.

In this case, the basic assumption of EMMA (i.e., the flux of micrometeorite scales as the declining flux of lunar impactors) becomes an ordinary ineluctable outcome of the early Sun being a DD-star with a relatively short lifetimes of ∼500 Myr, with regard to the wide range of values observed today –i.e., 10–20 Myr for the so called transition objects to 100–10,000 Myr for main sequence stars (see Greaves, her Table 1). Indeed, if one increases the number of comets, one also increases both the number of those with perihelion smaller than ∼2.5 AU that release interplanetary dust during the sublimation of their dirty ices and the number of giant comets that fragment into multiple bodies. It is plausible that the zodiacal cloud observed to day, which extends from near the Sun (F-corona) to at least 18 AU, is a tiny remnant of this earlier DD-Sun. We further discuss these topics in Sects. 23 and 24.

3.4 Reprocessing of Planetary Materials in Regoliths

More about thin regoliths on lunar mare. Lunar material returned to the Earth by the Apollo and Luna missions were collected in a loose layer of debris, which tops the entire lunar surface, and which is essentially made of 1–300 µm size grains. A regolith is defined as a layer of impact-fragmented and comminuted material, which only exists on a planetary surface that was not recycled by plate tectonics. On lunar mare, this comminution was induced by the local impacts of small bodies with size ≤10 m. They are far more abundant in number than the ≥500 m impactors, which produced the explosion craters with diameter of ≥4 km used to plot the variations $K(t)$ up to about 3.9 Gyr ago.

Repeated impacts also trigger a “gardening” of the regolith material through the deposition and/or the excavation of successive ejecta blankets originating from impact craters. During this gardening lunar material gets reprocessed, yielding several distinct types of interesting byproducts. One of them is composed of lunar “glassy agglutinates” that form when liquid glass splashes caused during impact fall back on the soil particles that they aggregate, and which darken the lunar surface. Moreover, impact gardening allows a fraction of the grains to be exposed for short durations ($\leq 10,000$ years) right on the top surface of the regolith. There, they became "gas-rich" because they were implanted with high doses of neon ($\sim 10^{-5}$ cc/STP per gram) from both the solar wind (SW) and the more energetic "solar energetic particles" (SEPs), which penetrate up to depths of about 50 nm and 100 µm in solids, respectively –in this odd unit used by geochemists 1 cc/STP of neon per gram of material corresponds to about 1 mg of neon per gram. They thus contain a dominant component of "solar" neon showing an isotopic composition ($^{20}Ne/^{22}Ne$ ratio) bracketed between the values measured in the SW and the SEPs, of about 13.8 and 11.2, respectively.

But they get also exposed for a much longer duration ($\sim$1 Gyr) in the top meter of the lunar regolith, which is irradiated by the much more energetic and penetrating galactic cosmic rays (GCRs). During this long exposure, they accumulate cosmogenic nuclides produced during the nuclear interactions of the GCRs with the constituent atoms of the grains –the most useful ones, at least in the case of the Moon, were ^{21}Ne, ^{126}Xe, ^{131}Xe and ^{138}Ga. Yves Langevin did trace back with a Monte-Carlo code the discontinuous depth history of individual grains in the lunar regolith, which allows us to describe the effects of this complex accumulation of solar neon and cosmogenic isotopes in the lunar regolith (Duraud et al. 1975; Langevin and Maurette 1976). As the predictions well fitted the corresponding observations the model could be extrapolated to asteroids with some confidence (Langevin, 1978; Bibring et al., 1975).

Lunar breccias are the most abundant rocks collected on the lunar surface, where the abundance of the small fragments of truly igneous rocks (i.e., those resulting from the cooling of a magma) is at most 1%. They are also typical products of regolith reprocessing that are formed during the shock compaction of the regolith upon impacts. An index of "maturity" of either lunar soil samples or the constituent grains of lunar breccias can be defined by looking for example at their proportion of neon-rich grains. The most mature soils and/or breccias show both a high proportion of gas-rich grains (about 50%), with solar neon contents of $\geq 10^{-5}$ cc/STP per gram. In contrast, in an immature soil collected in a younger crater ray excavated from a deep crater, the proportion of gas-rich grains drops to about 10%, because most of the grains were not exposed on the top surface of the regolith as to get a neon "sunburn".

The investigation of lunar breccias, as well as the computations of Langevin, greatly helped to understand that most stony meteorites originating from asteroids are also regolith breccias. They might include stones as different as differentiated meteorites made of basalts, and the volatile-rich hydrous–carbonaceous chondrites (HCCs), to which micrometeorites are only related.

A "grain-rain" on asteroids. As pointed out by Britt and Lebofsky (1999), for years top asteroid scientists did not believe that regoliths could be formed on small asteroids with sizes of a few tens of kilometers –the crater rays ejected from smaller asteroids could hardly fall back on the asteroid surface to build up approximately 1 meter thick regoliths. However, all three asteroids with sizes of about 20 to 50 km imaged from spacecrafts (Gaspra, Ida and Mathilde) have a significant regolith. Moreover, as soon as lunar breccias were investigated in the early 1970s, it was established that most stony meteorites thought to originate from interasteroidal collisions are also regolith breccias!

The existence of regoliths on asteroids has been further confirmed from their reflectance spectra (in the visible and near-infrared wavelengths) and their IR emission, which are strongly affected by the existence of a loose layer of debris (Hasegawa and Abe, 2001). This explains why most stony meteorites (with the notable exception of the approximately 30 Martian meteorites) are breccias, like most lunar rocks –the collection of 39 lunar meteorites only includes 5 small centimeter-sized chunk of igneous rock.

The major differences between the evolution of a regolith on the Moon and the asteroids over the last 4 Gyr have been discussed in particular by Langevin and collaborators (Langevin, 1981; Duraud et al., 1979; Langevin and Maurette, 1979; Dran et al., 1979). One of them is the acceleration of gravity ($\sim$1 cm/s^2), which is much smaller than on the Moon (162 cm/s^2). Consequently, most of the material ejected upon impact has a velocity exceeding the escape velocity, and this mass will be lost for the formation of a regolith. The regolith thus reaches an equillibrium thickness, $\Delta_E \sim 0.005 \times R_A^2/R_M$, where R_A and R_M are the radius of the asteroid and the Moon, respectively. Upon continuous meteoritic impact this limiting thichness will recess toward the interior at a rate dR_A/dt. Thus, for $R_A \approx 10$ km, the value of $\Delta_E \approx 2$ m is reached in 100 Myr. Then the regolith subsequently recesses to the interior with a speed of 10 m/Gyr.

The lunar regolith presents a stratified structure, with an average stratum thickness of about 3 cm. But the small value of the acceleration of gravity on asteroids drastically modifies the extent and thickness of the ejecta blankets. They are now spread over a distance which is about R_M/R_A times greater than on the Moon and no stratum should be expected. The grains ejected from impact craters are thus deposited individually as a steady “grain-rain”. The values of dR_A/dt implies that the exposure of the grains in the various flux of nuclear particles existing in the interplanetary medium(i.e., SW, SEPs and GCRs) are at least 10 times smaller than those inferred for the Moon.

Furthermore these grains would originate from a relatively fresh regolith, which was formed and consequently irradiated during the last few hundred Myr. The asteroidal soils would thus be somewhat similar to “immature” lunar soils. In particular they would contain about 10% solar gas-rich grains, which were implanted in both SW-Ne and SEP-Ne, in good agreement with the values observed in gas-rich meteorites (see Sect. 19.2). Langevin noted that this steady regolith evolution can be interrupted by the shock wave induced by a large impact, which can blow away the regolith at the antipodal point.

Moreover, the rocks found below the regolith of a approximately 1500 km asteroid ($\Delta_E \approx 1.6$ km), which represent about 99.5% of its mass, have been fully shielded from the shallow solar neon implantations, and they should not contain solar neon. This specific feature is used in Sect. 8.3 to invalidate the model attributing the formation of the atmosphere to the impact of a giant "wet" asteroid thought to be composed of a bulk material similar to that of the most water-rich primitive hydrous–carbonaceous chondrites, which are all regolith breccias contaminated by solar noble gases.

3.5 Scavenging of Highly Siderophile Elements During Large Impacts

Accordingly to a credible model (c.f., Rushmer et al. (2000)), highly siderophile elements (HSEs) in the Earth's mantle (i.e., iron loving elements such as iridium) are quickly scavenged by the impact of bodies that are too big as to be fully decelerated in the atmosphere. Therefore, they explode upon impact with the Earth and the largest ones produce pockets of liquid silicates, in which droplets of liquid iron nucleate.

Metal sinking to the core can take place remarkably quickly from this initial emulsion of liquid iron in melted silicates after a segregation of the droplets into large metal "diapirs" that pierce the mantle. David Stevenson of the California Institute of Technology (c.f. the quotation of Bettayeb et al. (2004)) estimates that a pocket of iron with a mass of 10^5–10^6 tons (i.e., corresponding to a ~100 m size stony asteroid containing 20 weight% of iron) will propagate at a speed of about 5 m per second. Therefore, it would merge the core in about one week of fast descent! In particular, it can be reasoned that the last giant planetary embryo that did form the Moon while merging the proto-Earth probably induced the last "terminal" scavenging of its own HSEs, thus preparing a clean niche for the post-lunar accumulation of micrometeoritic HSEs.

It should be noted that moderately siderophile elements such as Ni could get oxidized and trapped in minerals, thus being left behind during these impacts. In contrast, it is generally considered that sulfur did behave as a strongly siderophile element during the early history of the Earth. This would explain the lower density of the outer liquid metallic core of the Earth, attributed to a sulfur content of about 10%.

In this case, the residual HSEs now found in the mantle had to be delivered after the formation of the Moon by a late veneer of *small* extraterrestrial bodies, which could be fully decelerated before their impact on the Earth, as to avoid the formation of pockets of melted silicates that would initiate the scavenging of their own HSEs throughout the mantle. This is compatible with the deduction that micrometeorites dominated the delivery of extraterrestrial material to the Earth since the formation of the Moon (c.f., Sect. 7).

4 A Microscopic Suspect for the Formation of the Earth's Atmosphere

In accordance with Ozima and Podosek (2002), atmosphere will refer to all volatiles in surface reservoirs of the Earth, including air but also liquid and frozen water and sedimentary rocks, such carbonates, where early CO_2 is now trapped. Today, around 90% of the mass of air is found in the first six kilometers of the thick gaseous envelope of the Earth which extends to about 800 km, the altitude beyond which the magnetosphere exists. The mass of the oceans, which amount to about 97.2% of all terrestrial waters, would be equivalent to an aproxmately 2.7 km thick "film" of liquid water around the Earth (i.e., about 0.04% of the Earth's radius). For a comparison, the total mass of terrestrial living organisms would represent an equivalent thickness of around 10 cm and if the Earth was reduced to the size of an orange the oceans would represent one drop of water.

4.1 Beware of Visible and Invisible Shooting Stars

From the naked eyes to radar echoes. A shooting star (i.e., the colloquial poetic translation of a meteor trail) is roughly a short lived ($\leq$1 sec) cylindrical column of excited air molecules and ions constituting the high temperature meteor wake, with an initial diameter and length of a few meters and 10 meters, respectively (see also Sect. 16.4). This initial diameter of 2 m expands to about 100 m in less than one second! However, as this wake is constantly formed every second along the deceleration range of the incoming body (i.e.,*as long as ablation gases are ejected*) the apparent illuminated length of the shooting star is about 10–20 km in the thermosphere (Fig. 2).

Upon desexcitation these species emit light, which is detectable with the naked eye as a visible shooting star when the micrometeorite size is larger than a few mm (i.e., becomes a "minimeteorite"). However, smaller micrometeorites, down to sizes of a few μm, can be still detected as "invisible" Radar shooting stars with powerful radar telescopes, such as the Arecibo radiotelescope in Puerto Rico (Raizada et al., 2004).

Bodies bounded to the solar system move on elliptical orbit with the Sun at one focus, and they can be defined by several parameters including their eccentricity, which measures their departure from circularity. It varies from 0 to 0.2 for the almost circular orbits of main belt asteroids (found between

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Fig. 2. Three visible shooting stars from the 2001 Leonid meteor shower produced by meteoroids with size larger than a few millimeters, called minimeteorites in this work. The collisions between air molecules and the ablation gases percolating throughout the leading edge of the incoming meteoroid produced the short-lived high temperature meteor wake during collisions with air molecules (Courtesy Jerry Lodrigus, Villingboro Astronomical Society).

1.8 and 4.0 AU) to about 1 for the very elongated elliptical orbits of comets reaching the boundary of the Oort cloud at 50,000 AU. Other parameters used to define these orbits are the perihelion and the aphelion of these bodies, which measure their closest and farthest distances to the Sun, respectively.

An astonishing capability of astronomers is to use the 10–20 km long shooting star as a minuscule element of orbit. High performance computers work on this orbital element to re-construct the full orbit of the parent micrometeorite in space, which largely exceeds a few hundreds million km! When the speed of the incoming particles is determined with good accuracy, this orbit is sufficiently well characterized to know whether it looks like a typical orbit of asteroid or comet, which are statistically very different. From the statistic of about 100,000 well-characterized shooting stars, astronomers deduced in the 1960s that about 95% of the shooting stars correspond to the orbits expected for cometary micrometeorites.

A wrong initial bet that finally turned to be right? In 1980, we conceived our first project to recover for the first time large unmelted micrometeorites from Antarctic ices, where they had been preserved by deep freeze in ultra-clean ices. Our major bet, based on this impressive statistic of visible and Radar shooting stars, was that most micrometeorites with sizes exceeding the limit of sensitivity of the earlier radiotelescopes (about 100 μm) should be cometary dust grains. Smaller micrometeorites with sizes of about 5–15 μm, and coined as “IDPs” (Interplanetary dust particles), started to be collected in the stratosphere in 1974. They were too small to be included in the early statistic of Radar meteors and there was no clue about their origin.

We thus decided to focus on large micrometeorites with sizes ≥100 μm that leave a Radar meteor fingerprint. The Earth was thus assimilated to a “poor man” space probe to collect for the first time cometary dust grains, well before dedicated space missions such as *Stardust* (c.f., last Subsect. in Chap. 30). This was an exciting prospect, at a time when comets were considered to be the most primitive objects of the solar system, while meteorites were only second rate objects sampling less “primitive” asteroidal material –this was deduced from the asteroidal type orbit of the largest meteors penetrating much deeper into the atmosphere, and corresponding to the size of meteorites.

Ironically, a few years later, Jack Wisdom showed that the criterion of a cometary orbit is not reliable to identify the cometary origin of a particle! Indeed, Jupiter can “pump” gravitational energy into an initial almost circular asteroidal orbit to generate a more elongated elliptical orbit mimicking those of comets. However, Wisdom never reported an estimate of the proportion of cometary type orbits that would truly originate from asteroids, probably because this computation is too complex. Herb Zook went back and forth about this, sometimes estimating that it was as high as 50%.

To further confuse this issue, the more recent work of Liou et al. (1995, 1997) shows that dust particles ejected from specific type of periodic comets such as Temple 2 can be trapped in zones of the asteroidal belt corresponding to “mean motion resonance”(MMR)with the orbit of Jupiter, such as that defined as the 1/2 MMR, where the period of the trapped body is about one half that of Jupiter (see 4th Subsect. in Sect. 1).The particles are locked for thousands of year in such resonances where their orbits get circularized. When they escape the resonance, these ex-cometary particles now just look like asteroidal particles!

Nevertheless, after 10 years of studies, new arguments convinced us that most micrometeorites have indeed a cometary origin (see Sect. 22). This unexpectedly comforts our earlier bet, which looked wrong for about 20 years!

4.2 A New “Star” in the Cosmic Theater

Just by considering the two accretion stages outlined in Sect. 3.1 one already predicts that the early Earth’s atmosphere was quite complex. Indeed, during the second stage of accretion involving planetary embryos, in addition to its own volatiles degassed from its building material, the proto-Earth started to accrete nebular gases as well as volatiles released upon the merging of the embryos, as soon as its mass reached about 4 lunar masses –in this unit of mass our old contemporary Earth is worth ∼80 lunar masses. An additional contribution of the impacts of the most massive planetary embryos carrying their own atmosphere should also be expected.

To further complicate this issue, a period of *late heavy bombardment* of the Earth by asteroids, comets and left over planetesimals was ignited during this second stage of accretion. The cataclysmic explosion of such small approximately 10 km-sized bodies also fed the growth of the atmosphere. Finally, these small bodies released meteorites and interplanetary dust particles (IDPs) in the inner solar system, which were captured by the Earth as "juvenile" micrometeorites. Their volatilization and/or degassing upon atmospheric entry were also injecting additional components in the early atmosphere!

However, the Moon was soon to star in this cosmic theatre, to considerably simplify this expected tricky complexity of the early Earth's atmosphere. Its violent birth was a by-product of the impact of the last giant planetary embryo that did close the formation time interval of the Earth. Moreover, it is likely that it blew off the pre-lunar atmosphere of the Earth, thus preparing a new niche for a simpler post-lunar atmosphere (c.f., Sect. 29.2). Indeed, one would predict that after the Moon forming impact the young Earth was only bombarded by a "late veneer" of smaller bodies including asteroids, comets, left-over planetesimals and the debris that all these bodies ejected in the interplanetary medium during collisions and/or sublimation of dirty ices at heliocentric distances ≤2.5 AU. If one of these components turned to be the dominant one the composition of the atmosphere could be rather simple while showing a characteristic "purity" directly inherited from it.

4.3 A Giant Storm of Cometary Shooting Stars?

We got a few hints that comets, and not asteroids, could have played a major role in the formation of the post-lunar atmosphere –see Sects. 7 (3rd Subsect.) and 22.

However, another stringent condition is required. Any earlier mixture of volatiles trapped in the Earth's mantle, and which would be slowly degassed through volcanism, should not contaminate the cometary contribution. This implies that the degassing of the Earth mantle should have been almost completed at the time of formation of the Moon, near the end of $\Delta(Earth)$. Another radiochronometer ($^{40}Ar/^{36}Ar$) shows that we are on the right track (Sarda et al. 1985; Ozima and Zahnle, 1992; Ozima and Kudo, 1972).

There is still a problem. The delivery of volatile species by comets could have involved either their direct cataclysmic impacts with the Earth, or the capture of the enormous flux of dust that they released during the sublimation of their dirty ices in the inner solar system at heliocentric distances ≤2.5 AU. Astronomers have recently measured the isotopic composition (i.e., the D/H ratio) of the constituent water of three comets originating from the Oort cloud. Their D/H ratios are about two times higher than the standard terrestrial value "SMOW", defined for an *average* of the terrestrial oceans. Therefore, the direct hit of comets could not have delivered more than ∼10% of the total mass of the oceans if these high ratios are further confirmed for comets from the EdK belt –c.f., Morbidelli et al. (2000) for a summary of this work.

An astonishing vision emerges from these qualitative deductions, essentially based on the computations of planetary dynamicists, the theory of formation of the Moon, noble gas chronologies and the physics of the impact of the giant Moon-forming body. The atmosphere of the early Earth was possibly produced by a long lasting giant "storm" of cometary interplanetary dust particles (IDPs) due to a late arrival of comets in the inner solar system. This storm ignited a new type of diffuse volcanism "falling from the sky", and fed by the volatilization and the degassing upon melting of these volatile-rich IDPs during their sharp aerodynamical braking with air molecules. One of the major purposes of this book is to describe how we strengthened this qualitative suspicion about this microscopic suspect. This took us about 15 years of a remarkably inefficient work in the meanderings of the obscure first 500 Myr history of the Earth.

Problems in semantics. Some of my colleagues resent the use of "volcanism" to describe a major effect of early micrometeorite accretion. Indeed, this word should be strictly reserved to something originating from planetary interiors, i.e., below your shoes and not from above your head. Beautiful and poetic words like volcanism should stay alive while extending their range of applications. Look at volcanic, used for example in a volcanic love affair.

I was opened to any suggestion but so far I collected odd acronyms such as:

- *MMR*, for micrometeorite rain;
- *MMI* for micrometeorite invasion;
- *MMA* for micrometeorite attack;
- *COCTE*, for "*Cette Obscure Clarté qui Tombait des Etoiles*" quoted in a famous tragedy (Le Cid) of the French Pierre Corneille (written in 1637). Although the last French acronym sounds pretty good, the approximate English translation, *TOGFS* ("*This Obscure Gleam that Fell from the Stars*") just sounds terrible. I shall stick to *volcanism* in this book.

Furthermore, US colleagues have a long tradition to call the tiny micrometeorites that they collect in the stratosphere as *IDPs* (Interplanetary Dust Particles). This might be misleading as it would somewhat implies that they did not get altered upon atmospheric entry, and that they thus suffered an "intact" capture. This is not so. Powerful radar telescopes, such as the 300 m dish Arecibo radar in Puerto Rico, can detect micrometeorites down to a very small size of 1–10 μm through the ablation gases percolating throughout their leading edge, and that form a "wake" detectable by the radar (see Sect. 16.4). Therefore, in this book, they will be just quoted as SMMs (Stratospheric MicroMeteorites).

Finally, while I was trying to avoid writting a brand new book during the correction of the first proof-reading of this book, I was horrified to see the text flooded with $\sim$, $\approx$, about, around, approximately. Therefore, I decided to randomly suppress at least 50% of them.

4.4 A Decisive "Rendez-Vous" with Antarctic Micrometeorites

The turning point of our cosmic detective investigation was the availability of large *unmelted* micrometeorites that we recovered for the first time from Antarctic ices in December 1987, and which will be quoted as AMMs from now on. Then, they could be meaningfully compared to the $\sim$135 groups of meteorites –c.f., Sect. 6.3.

Their studies led to the three following stunning observations that support the role of micrometeorites in the formation of the atmosphere:

- About 90% of the AMMs are made of a volatile-rich hydrous–carbonaceous material;
- the chemical composition of volatile species in the terrestrial atmosphere, formed about 4.4 Gyr ago, and which weights about 2.10^{24} g, is strikingly similar to that of the "puff" of atmosphere that would be released upon the degassing of a $\sim$5 mg aliquot of about 500 AMMs, which were individually analyzed over a period of $\sim$10 years as to characterize the chemical and isotopic composition of micrometeorites recovered from about 50,000 year old Antarctic ices;
- from all extraterrestrial material analyzed yet, only the isotopic composition of the constituent water of the hydrous silicates of AMMs give the best fit to the corresponding SMOW value measured for an average of the terrestrial oceans (c.f., Sect. 9.2).

After this kind of long introduction to "Micrometeoritics" that allowed to present the major actors and define most of the key words used in this book, we next turn to the collections of extraterrestrial materials on the Earth and outline major similarities and differences between micrometeorites and meteorites. A brief history of this science, which deals with an obscure dusty contamination of the Earth falling from the sky, is more appropriately given in the Epilogue.

Part II

"Primitive" Extraterrestrial Matter on the Earth

To conduct this kind of cosmic detective investigation, we decided in 1982 to collect and analyze Antarctic micrometeorites ourselves, in order to control every step in their study. Moreover, we had to get familiar with the collection and study of meteorites, and the handling of Antarctica ices in ultra-clean conditions. In 1982 we conceived our first project to recover for the first time large unmelted micrometeorites from ultra-clean Antarctica ices, where they would be preserved by deep freeze at the first place. Our bet was that they would turnout to be cometary dust grains, at a time when it was believed that comets were the most primitive objects of the solar system, and that meteorites were only a sampling of the constituent material of less primitive asteroids. The Earth was thus exploited as a poor man's space probe in hopes of collecting for the first time cometary dust grains, well before dedicated space missions such as "Stardust".

5 The Space Collector "Earth"

5.1 Dark Stones in Cold and Hot Deserts

When they are ejected into the interplanetary medium during interasteroidal collisions, meteorites have a limited lifetime in space, which is scaled by their "cosmic-ray exposure ages" inferred from the concentrations of cosmogenic nuclides such as ^{3}He, ^{21}Ne and ^{38}Ar, produced during the nuclear reactions of galactic cosmic rays with the constituent atoms of meteorites. Such ages range from about 10 to 500 Myr, with the notable exception of the shorter age of the CI- and CM-type hydrous–carbonaceous chondrites (see Sect. 22.3). Consequently, meteorites have to be constantly replenished upon interasteroidal collisions.

They have been recognized as extraterrestrial stones over the last 1300 years. Indeed, there is a preserved fall in Japan from about 700 AD. Since then, they started to be purposely collected and investigated. These activities define the exotic field of Meteoritics that enlightens the life of scientists dubbed meteoriticists. The specific journal of this discipline is titled *Meteoritics and Planetary Science*. Today, there are probably about 70,000 meteorites in the major world collections, representing about 3000 distinct meteorites, because meteorites often break up into several similar fragments during their flight in the atmosphere –this constitutes the phenomenon of "showers". The 4 major world collections rank as follows with regard to their total number of meteorites: (1) Smithsonian Institution, Washington D.C., (2) British Museum (National History), London, (3) Naturhistorisches Museum, Vienna, and (4) Museum d'Histoire Naturelle, Paris.

All the monographs written about meteorites include a lengthy chapter about their collection. So, only a few major features of these collections will be outlined hereafter. One distinguishes the finds (i.e., meteorites simply found on the Earth's surface) from the falls, which are first observed as shooting stars, and collected soon after their fall. The falls are much less abundant than the finds but they are the most coveted meteorites, because they have not generally been subjected to extensive terrestrial weathering, and volcanic and/or man-made contaminations, such as acid rains.

Ernst Chladni was the first in the western world to both demonstrates the extraterrestrial origin of meteorites and to collect them systematically (1808). He is at the origin of modern meteorite research (see Marvin, 1996).

M. Maurette, The Space Collector "Earth". In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 31–53 (2006)
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The book of Harvey Nininger (1972) is a beautiful recollection of his own experience as the most passionate hunter of meteorites of all time. He did continue collecting meteorites even during the big depression of 1929 and established the record of 218 distinct finds and 8 falls, amounting to about 2000 meteorites after 30 years of hunting.

His record of falls has never been surpassed. However, John Schutt, after about 30 field seasons in Antarctica with ANSMET (i.e., the US program of "Antarctic Search for Meteorites"), did beat his record of finds. From 1976 until 1990 William Cassidy was the leader of these highly successful US hunts for meteorites in Antarctica. He thus became one of the greatest hunters of finds of all time with a record of about 10,000 fragments of meteorites. Ralph Harvey took the difficult succession of Cassidy. Maurette (1993) presented a summary of the passionate life of both Nininger and Cassidy. Burke (1986) gave an impressively good detailed description about the search and studies of meteorites until 1986. We were all awaiting the book of Cassidy, as to know better about the adventures of this king of the finds hunters in the cold. It was published 2 years ago. It relates passionate adventures in the coldness of the blue ice fields of the Transantarctic mountains, where a French colleague (Paul Pellas) discovered that the French Bordeaux wines experienced a fast but good maturation! But it also outlines, in a gentle manner, some bitter fights with powerful colleagues. They first predicted that Cassidy "*would not find any*", and rejected the proposal tree times. Luckily, one month after the third rejection, the proposal got finally accepted, because a Japanese team reported the collect of 663 Antarctic meteorites! But Bill was too much successful with his program ANSMET (*Antarctic Search for Meteorites*), and the same colleagues got jealous. Fortunately Bob was still around to support vigorously this program. About 10 years later, they started to make troubles again! Anyways, altogether with the collects of our Japanese colleagues (that started in 1969), and after 27 years of ANSMET, there are about 30,000 Antarctic meteorites available for studies. Before these collects, there were $\sim$20,000 meteorites. Then, over the last 10 years, expeditions mostly organized by professional traders in hot deserts such as the Sahara, were also highly successful, and they yielded $\sim$20,000 additional meteorites. There are about 70,000 meteorites in the world collections!

The overwhelming number of finds has been recovered from both cold and hot deserts. The major reason is that meteorites can accumulate over long periods in such deserts, in particular because their rate of weathering is limited by the low water content of the atmosphere and ground. The major limitations in hot deserts are climatic variations, which can flood them as to limit the life expectancy of meteorites to about 100–200 centuries-in our temperate zones this value catastrophically drops to a few centuries. In Antarctica the air is even drier, meteorites are further preserved by deep freeze, and climatic variations that would melt the ice are less frequent. There, meteorites can accumulate over the longest periods that can reach $\geq$2 Myr!

In these deserts fresh meteorites will look like a black to brown stone (Fig. 3). Upon atmospheric entry they get melted and can loose up to 90% of their initial mass upon ablation. On stony meteorites, the scar of this ablation is a glassy shining black fusion crust with a thickness of up to a few tenths of a millimeter. Most of the time, if the meteorite shows a fresh internal fracture surface, it will reveal a light internal section. With a simple magnifying glass these internal surfaces will show in about 80% of the cases small rounded objects, not observed in terrestrial rocks, called chondrules (see Fig. 12 in Sect. 6.1). Simultaneously, the same meteorites will be sufficiently magnetic as to attract the needle of a compass. If these three simple criteria are satisfied one is almost certain to have collected a meteorite.

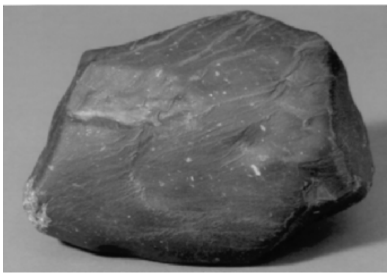

Fig. 3. Lunar meteorite discovered in the Sahara desert that is coated with a typical dark fusion crust with a thickness of a few hundred μm. Meteorites can loose up to 90% of their initial mass upon atmospheric entry. This "ablation" loss efficiently cools down the residual meteorite hitting the Earth's surface at free fall velocity (Courtesy G. Kurat).

However, if you search only for stones with a black gloss you will miss a lot of meteorites, because it gradually fades away with time as it gets slowly weathered. In fact, the first rule for searching for meteorites in the blue ice fields bordering Transantarctic Mountains, and cluttered with moraine debris, is to get very familiar with local terrestrial rocks. Once the eye is trained, meteorites will be readily spotted as *being different from the local rocks.*

Even meteorites retrieved from Antarctica present some specific weathering. During the short Antarctic summer a dark stone is preferentially heated up by solar radiation. A thin layer of melted ice water is thus in contact with the stone that trigger an efficient hydrous alteration (coined as "cryogenic" in this book) that can penetrate right to the center of the stone. In particular, ordinary chondrites initially contain small inclusions of an alloy of iron and nickel. In Antarctica, all these inclusions are transformed into terrestrial rust, which cannot be used any longer for scientific investigation. In brief, cryogenic weathering has to be well assessed if one wants to meaningfully exploit materials retrieved from Antarctica, including not only meteorites but also micrometeorites recovered from blue ices (see Sect. 5.4), in particular in the field of exobiology.

The rule of thumb for predicting the number of meteorites in a hot desert is to know first about the lifetime of the top surface of the desert against strong climatic variations. For example, this value is about 200 centuries for the Great Eastern Erg in Algeria. Combining it with the number flux of meteorites (about 30,000 for the whole Earth, per year) one ends up with about one meteorite, per km^2, per 200 centuries. Therefore, even in this very favorable Algerian Erg, one would have to search through about $1\,km^2$ just to discover one!

Fortunately, several processes can further increase the surface concentration of meteorites. This happens in Antarctica in the so-called stranding blue ice fields, where the highest number of meteorites has been found. When the ice flow formed in Central Antarctica moves to the sea, it can hit an obstacle such as a Nunatak (i.e., a still partially buried mountain). The flow is deflected upward, and intersects the ice surface where it got quickly ablated during the short Antarctic summer but also at a smaller rate all the year-round. Thus, meteorites are constantly pouring on the resulting "stagnant" ice surface, where they accumulate.

In hot deserts, concentration processes are also effective. For example, in Roosevelt County (New Mexico), Ivan Wilson decided to search every square meter of a bush-covered area of about $0.1\,km^2$. In five years, with the help of two colleagues, he thus found about 160 meteorites. For comparison, in one field season lasting about 2–3 weeks, the team of Cassidy (about half a dozen people) can collect over 1,000 meteorites. The unexpectedly high number of meteorites was likely related to a recommendation of the US Department of Agriculture in the 1950's advising farmers to till all soils. A subsequent short windy drought late that year stripped away the soil, thus leaving behind a hard light colored terrain and desperate farmers. Thus, meteorites originally scattered in the top soil get uncovered and concentrated on this terrain as to be "easily" hand-picked!

5.2 Micrometeorites in the Stratosphere and Deep Sea Sediments

The collections of unmelted micrometeorites and cosmic spherules (i.e., micrometeorites fully melted upon atmospheric entry) are more recent than that of meteorites. Consequently they have been little advertised in books addressed to general audiences. Hodge (1981) has beautifully reviewed the history of collections until 1980. The collections made in deep sea sediments and with the stratospheric aircrafts of NASA, since 1974, have been presented by our US colleagues in several review papers (Brownlee, 1985) and in books (Zolensky et al., 1994). However, beside our own books (Maurette 1993: Kurat and Maurette 1997), the recovery of micrometeorites from both Greenland

and Antarctica was not described in detail. Recent research papers present new successful attempts to collect Antarctic micrometeorites (Taylor et al. 1998; Taylor et al. 2000,2001; Nakamura et al. 1999; Yada and Kojima 2000; Duprat et al. 2004.)

Until 1974: a multitude of unsuccessful attempts to recover unmelted micrometeorites. Since the first collect of cosmic spherules by the 1873–1876 Challenger oceanographic expedition, many groups have attempted to collect unmelted micrometeorites on the Earth, in sites as varied as, deep sea sediments, sand beaches, lake bottoms, the Greenland and Antarctic ice sheets, roofs of buildings, swimming pools, the stratosphere, etc.

The French Lucien Rudaux was certainly the most passionate hunter of micrometeorites between about 1920 and 1935. He conceived many micrometeorite collectors and he wrote a beautiful old style book about planetology (Rudaux, 1937). For example, in the garden of his villa on the Channel Coast of France, near a small town (Etretat), he did deploy frequently a kind of meter-sized dish to specifically catch particles of meteor showers. He also went to the snowy slopes of the French Alps where he had the key to a shepherd hut. He was using with the greatest originality and conviction his personal coffee pot to collect micrometeorites (Fig. 4). He melted the snow with the coffee pot and then filtered melt snow water on the paper filter as to get a kind of micrometeorite coffee! He was in fact the grandfather of the much larger scheme that we started using at Cap-Prudhomme in December 1987 to melt 200 tons of ice!

However, until 1974 these collections were not successful, except for yielding cosmic spherules including both stony and iron–nickel objects. In fact, besides cosmic spherules with their typical rounded shapes, there was no good criterion to identify quickly a rare extraterrestrial irregular dust grain in terrestrial sediments. An even the population of spherules was frequently heavily contaminated by terrestrial spherules!

Indeed, these collects face severe difficulties, beside the fact that these dust grains, contrarily to meteorites, are just invisible with the unaided eyes. They include a gigantic contamination by terrestrial grains, the low flux of micrometeorites (about one micrometeorite with size of $\geq 100\,\mu m$ per m^2 per year), and their very short life expectancy in our temperate countries, as a result of a strong terrestrial weathering, particularly exacerbated by acid rains. Thus, a micrometeorite residing on a roof would be transformed into a tiny chunk of useless terrestrial clays in a few years.

Only modern collections made since 1974 will be considered, proceeding first from the stratosphere to the middle of the Pacific, and then to the giant Greenland and Antarctica ice sheets. But we have also used studies of the micrometeorite flux in the interplanetary medium by our colleagues, with techniques including:

Cl. L. Rudaux.

Récolte des corpuscules magnétiques dans l'eau de fusion de la neige fraîche.

Fig. 4. Francois Rudaux, an amateur astronomer, had an impressive passion for astronomy and shooting stars (Rudaux, 1937). He was mostly active in 1920–1935, when he developed various schemes to collect particles from meteor showers. Here, he is in full action in the Alps in the 1920s smoking a cigarette, while filtering melt snow water prepared in his coffee pot. Amazingly, the paper filter used in these earlier times looks very similar to those that we can still buy today. In the 1920s, due to the general ignorance about cosmic dust and the danger of cigarette smoking, we would have also melted a small amount of snow while smoking a cigar. But we know today that cigarette smoking is dangerous not only for your health but for the collection scheme used by Rudaux because fly ashes from the cigarette can look very much like modern micrometeorites. We also know that if we filter several thousand coffee pots of melted snow water in the cleanest area of the Alps (and not around the summer hut of a shepherd where the snow is dirty), we might collect one micrometeorite diluted in more that 10 million terrestrial dust particles.

– micrometeorites collectors exposed for about 5 years at $\sim$300 km above the Earth on the LDEF spacecraft (Long Duration Exposure Facility);
– micrometeorites detectors on board the Galileo spacecraft;
– in-situ analysis of the dust tail of the Halley comet;
– telescopic remote sensing of silicate grains in the tail of the Hale–Bopp comet.

From 1974 up to now: Successes while flying in the stratosphere. Donald Brownle was a young astronomer trained in nuclear physics. He revolutionized the collection of micrometeorites in the early 1970s. In particular, he was the first collector to use reliable modern criteria to identify the extraterrestrial origin of a tiny irregular dust grain.

After various balloons experiments that he started to plan in the 1960s –one of them in 1973 was dubbed the "vacuum monster"– he successfully made a milestone collection with a NASA aircraft in 1974, right in the lower stratosphere (Brownlee et al., 1977). In fact, to minimize a huge terrestrial contamination by wind-borne dust, micrometeorites have to be collected in the cleanest areas of the world, which are the stratosphere, the center of the Pacific and the very clean Greenland and Antarctic ice sheets. These remote zones are rarely reached by wind-borne dust generated on the continents, which gravitationally settle before reaching them. But they can still be contaminated by large volcanic eruptions.

A small collector plate ($\sim$60 cm^2) was fixed under the wing of a U2 stratospheric aircraft. This plate was coated with an approximately 100 µm-thick layer of viscous silicone oil. When the aircraft reached an altitude of about 20 km, this plate was exposed, and in a few hours of flight (at speeds of 900 km an hour), a huge volume of air was swept by the plate. The lightest porous "fluffy" particles, which have the slowest rates of gravitational settling, preferentially accumulate in the stratospheric air. The U2 plates thus preferentially capture them when they hit the layer of silicone oil, fragmenting into cluster particles. But hard particles might bounce back to space. Back to Earth, the particles are extracted from the silicone oil and then rinsed in liquid freon and/or hexane as to get rid of the oil.

Then this technique was routinely used since 1981 within the NASA Cosmic Dust Program, relying on NASA ER-2 and WB-57F aircrafts flying in the lower stratosphere at elevations of 17–19 km (c.f., Brownlee (1985); Warren and Zolensky 1993). Up to today, numerous flights have been made. They yielded a collection of many thousands of small chondritic particles with sizes of about 5–20 µm (Fig. 5), which turned to be astonishingly interesting (c.f., Sect. 26 and 27). Our US colleagues have coined them "IDPs" (i.e., interplanetary dust particles). However, in this book, they will rather be called (**S**tratospheric **M**icro **M**eteorites) SMMs, for reasons outlined in Sect. 4.3.

A single 200 µm size micrometeorite selected in a typical daily collection of about 2000 Antarctic micrometeorites with sizes mostly ranging from 50 to 200 µm thus contains an amount of material larger than that of the whole early stratospheric collection recovered until 1989. But in 1990 a collector about 5 times larger ($\sim$300 cm^2) was used, which yielded a much larger number of SMMs, now including particles with sizes up to about 100 µm. Furthermore an astonishing set of complementary collection biases probably ended up concentrating in this collection the most fine-grained micrometeorites,

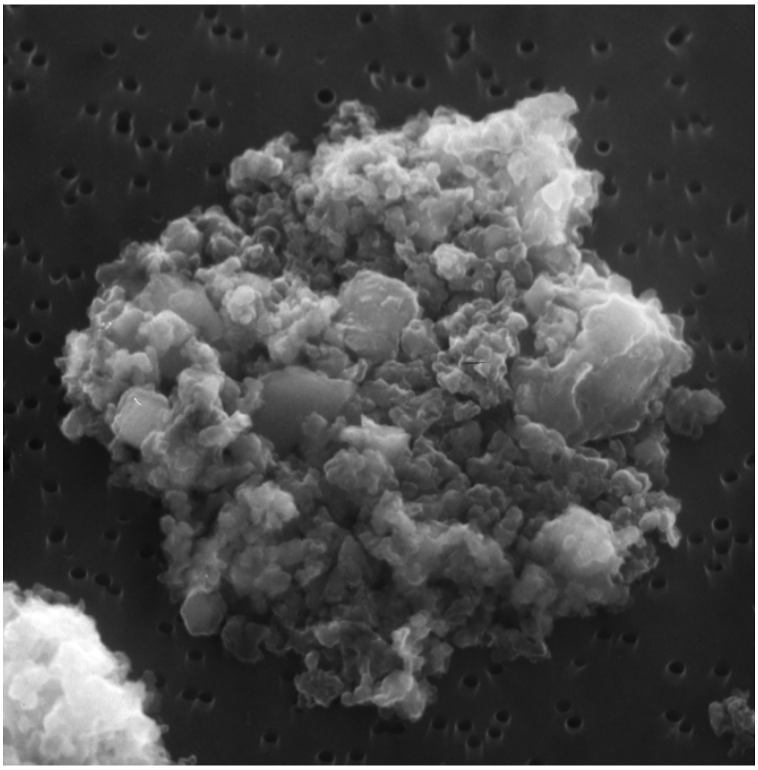

Fig. 5. Scanning electron microscope (SEM) observation of a stratospheric micrometeorite with a size of about 20 µm, which was collected by a stratospheric NASA aircraft at an altitude of about 20 km. It belongs to the class of the *chondritic–porous* particles essentially made of the finest anhydrous silicate grains ever observed in any type of extraterrestrial matter, including Antarctic micrometeorites and primitive meteorites. With this peculiar surface structure, which is rough on a submicron-sized scale, the particles were much better dragged to the collector plates of the aircraft by air turbulences, and they thus got preferentially enriched in the SMMs collection. The same surface structure also allowed their more efficient cooling upon atmospheric entry (Courtesy M. Zolensky).

which are possibly the most primitive, but not the most representative set of micrometeorites (see Sect. 26.3).

Recovery of a few hundred thousands magnetic cosmic spherules from deep-sea sediments. The first successful flight of the U2 aircraft in 1974 revealed the existence of small magnetic cosmic spherules (i.e., melted micrometeorites). In 1976 Brownlee built a giant magnet of ∼300 pounds, called the "cosmic muck rake". It was fastened to a ∼5 km-long cable and pulled across the sea floor, in order to drag magnetic particles trapped in deep sea sediments right at the center of the Pacific. It thus greatly improved the first successful attempt of the Danes (Brunn et al., 1955), by relying on both a much larger and efficient magnet as to "industrialize" this collection, and a cleaner area. After several rakings, he thus got a huge number of large (≥200 µm) melted magnetic micrometeorites, called cosmic spherules (Fig. 6) altogether with a minute amount of particles with irregular shapes, which were called unmelted micrometeorites.

Unfortunately, these micrometeorites, which were looking quite promising when they were first quickly described (Brownlee et al., 1980) –some of them were even quoted as being rimmed with a 2–10 µm thick magnetite rim– were not used in subsequent works. Therefore, pictures and/or chemical analyses are not available to correlate them to AMMs. This is probably due to both their scarcity and their extensive weathering in the interstitial water of deep-sea sediments, which is known to be quite corrosive. As they were collected with the magnetic rake they necessarily belonged to the class of the most magnetic unmelted particles, which were the most strongly heated up upon atmospheric entry as to be loaded with magnetite, and thus transformed into scoriaceous-type particles. In his latest review, Brownlee (2001) even mentions "the paucity of unmelted particles in deep sea sediments". This suggests that they weather rapidly in the sea floor environment but this is difficult to assess. The upper limit of their concentration in the deep-sea collection of spherules, which is hard to evaluate, is probably about 1 % (see Sect. 22.2).

At this time it was thought that this low abundance of unmelted micrometeorites was very compatible with the pessimistic predictions of models of atmospheric entry, where most micrometeorites would be melted by frictional heating with air molecules. But when we started to recover our first micrometeorites from Greenland and Antarctica ices, we found that the proportion of unmelted micrometeorites was much higher than predicted, reaching a value of around 25% in the ≥100 µm size range. Very recently, our new Concordia micrometeorite collection (see next section) yielded a value of 50%! In brief, due to both such strong magnetic collection biases and weathering unmelted micrometeorites from the deep-sea collection have not been used, yet, for scientific investigations.

5.3 Micrometeorites on the Greenland and Antarctic Ice Sheets

Cryoconite at the latitude of Sondrestromford (1984, 1987). About 10 years after the first stratospheric collection, we worked with teams of glaciologists –leaded by the Dane Claus Hammer and the Frenchman Michel Pourchet– to find elusive large unmelted micrometeorites with sizes ≥100 µm. We relied on the Greenland and Antarctica ice sheets as gigantic, ultra-clean, inexhaustible and cheap "space collectors" of micrometeorites. One of their

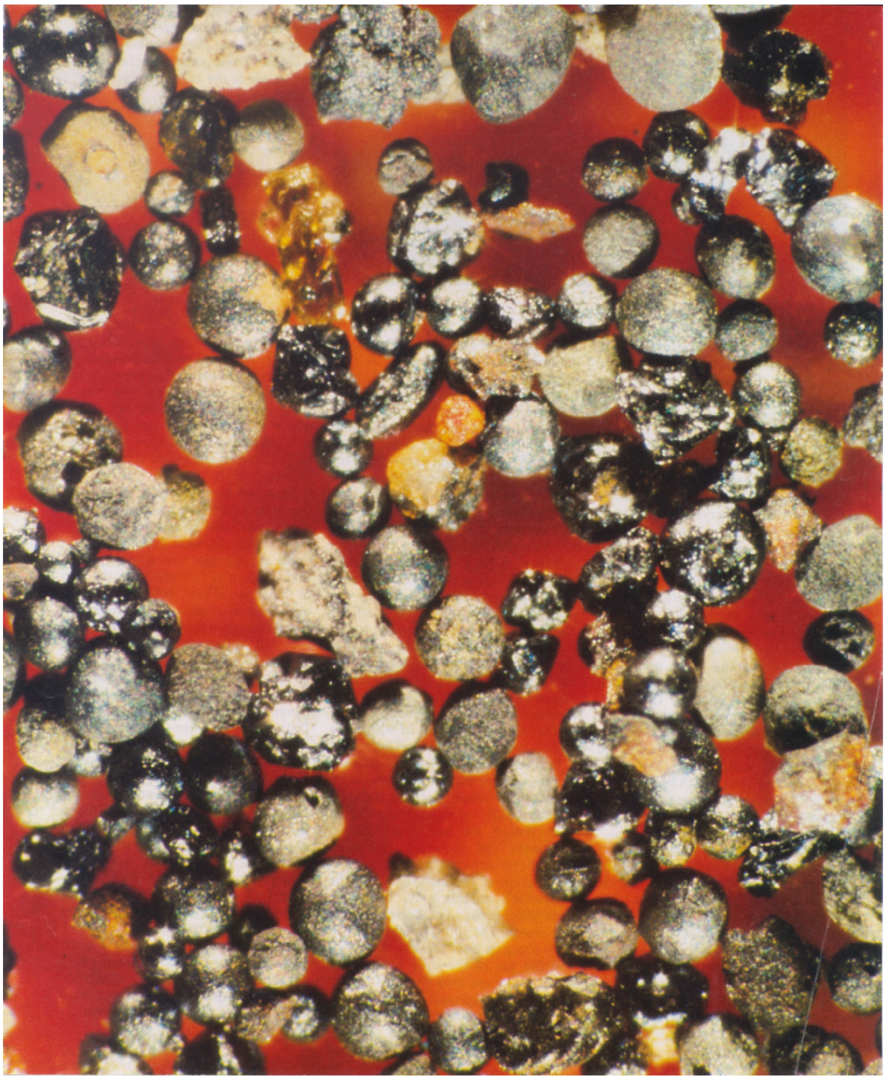

Fig. 6. Collection of cosmic spherules with size of $\geq$ 200 µm dragged with a 300 pound magnet in deep sea sediments at the centre of the Pacific ocean at a depth of about 5000 m. This collection contains a small proportion ($\sim$1%) of hard scoriaceous-type magnetic micrometeorites that could survive the harsh magnetic dragging (Courtesy of D.E. Brownlee).

Fig. 7. *Blue Lake I* expedition on the melt zone of the West Greenland ice sheet in June 1984, at about 20 km of the margin of the ice sheet, at the latitude of Sondreströmfjord. This glacial lake forms every year at the same location on the ice flow, which ablates at a rate of about 1 m/year. The team included five participants (C. Hammer, M. Maurette, K. Rasmussen, N. Reeh, H.H. Thomsen). In this picture they get prepared to vacuum up the dark deposit of cryoconite on the bottom of the lake with the hope that it might contain a large number of unmelted micrometeorites (Courtesy C. Hammer).

great advantages is that the ice collector material is very clean and can be eliminated quite easily by melting the ice at a few degrees Celcius.

In July 1984 we were left by a helicopter right on the ice, at about 20 km from the margin of the West Greenland ice sheet, at the latitude of Sondrestromfjord, in order to launch the "Blue Lake I" expedition. However, the pilot of the helicopter could not land at the carefully selected but rough spot, and we got lost for about one week, walking every day for long hours in order to find another beautiful blue lake (Fig. 7). There, we camped for about two weeks right on the ice, to attempt collecting for the first time large unmelted micrometeorites deposited on the bottom of the lake. This collection, which was successful thanks to the help of our four Danish colleagues, was going to greatly facilitate the allocations of funding for our future operations in Antarctica.

Our project originated from an observation of stereoscopic aerial photographs which revealed that this lake was fed by fast torrents running down the shallow slopes of an ice collection basin with a diameter of about 3 km. The measurements of the rates of ablation of the ice during the short Arctic summer (∼1 m per year) were made in the same area by one of the participants, Henrik Thomsen, of the Greenland Geological Survey, who knew very well this melt zone. They indicated that these torrents were pouring an enormous amount of melted ice water in this lake, about 100 million tons each year. This water was then flowing through the lake before feeding a spectacular and fast river called a bedière –this river moving at an impressive speed of about 3 m/s, ended up being "swallowed" about 2 km downstream in a approximately 800 m deep giant ice funnel.

However, such *melt* lakes form at the same position each year because they reflect the hill-valley structure of the basement rocks on which the ∼1 km-thick layer of ice flows like a very viscous fluid. As this process can be repeated for centuries, billions of tons of melt ice water should have dragged on the bottom of the lake micrometeorites, which were initially deposited in the formation zone of this gigantic amount of ice (e.g., much further away at about 500 km from the margin).

Our objective was to recover dark sediments dubbed cryoconite from the bottom of the lake, expecting that they should contain large unmelted micrometeorites. For this operation we had to rope ourselves and walk on the bottom of the lake (Fig. 8), while vacuuming up cryoconite using a hose connected to a plastic pump weighing about one pound (usually used to empty the heads in pleasure boats). Nobody apparently had the curiosity to walk on the bottom of such lakes in fast current. We were a bit worried. Suppose that the bottom was made of either a delicate structure that will crush under our weight, or of treacherous cutting ice stalactites. Finally, we found that it was just an extremely slippery icy bottom with a multitude of shallow ∼1 cm deep holes, where cryoconite was deposited and thus shielded from the fast current. We thus collected about 20 kg of cryoconite.

We found that these sediments were made of cocoons of filamentary siderobacteria with sizes of up to about 1 mm, in which mineral grains are encapsulated (Callot et al., 1990). We had thus to learn to disaggregate the tightly woven filaments of the cocoons in the laboratory, in order to release about 6 g of glacial sand with sizes ≥100 μm per kg of cryoconite. This amount of sand in turn yielded about 750 cosmic spherules and 250 unmelted micrometeorites, respectively, with sizes ≥100 μm. As for fresh meteorites stranding on a blue ice field in Antarctica, micrometeorites appear in the glacial sand as dark particles with irregular habit, which don't show any bright color and/or sharp edges. We learned a few years later that this dull luster originates from the fact that about 99% of them are only related to the hydrous–carbonaceous chondrites, which are dark inside.

But the whole melt zone of the Greenland ice sheet is just loaded with the so-called "cryoconite holes" with diameters ranging from a few mm up to a saturation value of a few meters –this saturation value reflects the lifetime

Fig. 8. Two of the participants (H.T and M.M) get cold feet and cold fingers collecting cryoconite with a hose linked to a light plastic pump weighting about one pound (usually used to empty the heads in pleasure boats) activated on the shore by our colleagues. While roping ourselves we could walk in the fast running water on the slippery icy bottom of the lake. (Courtesy C. Hammer).

of the holes against their destruction when the flow of their host ices hits a crevasse and/or a bedière, which washes them out. A few mm-thick layer of cryoconite is deposited on their bottom at a depth of about 25 cm corresponding to the penetration of the solar thermal wave. Surprisingly, this cryoconite, which can easily be recovered (without being tied with a rope in a fast current of cold water at about 0°C), contains the same concentration of micrometeorites as those deposited on the bottom of the lake, and which are much more dangerous to collect!

This shows that the concentration of micrometeorites builtup to saturation right at the start in the cryoconite holes, which finally end up being washed out of their cryoconite when their host ice flow intersects the lake. Thus, our work clearly showed that there is an inexhaustible amount of micrometeorites easy to recover on the melt zone of the Greenland ice sheet, right under your feet, because the melt zone supporting our feet and our tents is essentially made of cryoconite holes –not a pleasant location for camping!

Successful boyscouts at the latitude of Port-Victor (1987). We still pursued the collection of cryoconite samples with the Danes in Greenland, in 1987 and 1995, with the view of understanding how to find the best cryoconite deposits –i.e., the most enriched in micrometeorites. It was finally found in

1987, at the latitude of Port-Victor, about 600 km North of Sondrestromfjord, still on the West Greenland ice sheet. However, the collection was not made by us, but by a team of 12 year-old boy scouts from both France and Greenland, led by a guide, André Drouin (Fig. 9). They went very easily and quite cheaply on an ice field with safe access by foot, which was discovered by the French Polar Expedition of Paul-Emile Victor during the 1951 Geophysical year. Members of this expedition further built the wooden hut near the sea shore, used now by the kids for a nice summer vacation.

Drouin called me before the expedition as to ask if I had a suggestion about a little scientific project that the kids could perform there. I then advised him to buy a hand pump (e.g., the specific model used to empty the

Fig. 9. These twelve-year-old boy scouts met through the pairing of a French village with a Greenland village. They used to meet every year during the summer, either in France or in Greenland. In 1988 it was the turn of the French boys to go to Greenland. The project was to repair a hut built in 1958 by the French Polar Expedition of Paul-Emile Victor, at the latitude of Port Victor (about 600 km North of Sondreströmfjord). In July 1988, still with the same system of pumping, which was bought in a Greenland grocery store, they collected the best sample of cryoconite yet found (about 2 kg), under the leadership of their guide André Drouin. The reason is that the ice field extends to the seashore. Therefore, the ice is much better shielded from wind borne dust than at Sondreströmfjord, where the margin of the ice field is about 30 km further inland. Consequently, the amount of terrestrial sand per kilogram of cryoconite was about five times smaller, and it was much easier to find micrometeorites (Courtesy A. Drouin).

heads in pleasure boats, which worked so well) in the nearest grocery store in order to vacuum up a few large cryoconite holes, and return the samples of cryoconite to me (about 2 kg). We subsequently found that the glacial sand extracted from this "Port-Victor" cryoconite is the richest in micrometeorites. The reason is that the host ice of the holes flows right into the sea. The holes are thus efficiently shielded from any wind-borne terrestrial dust. In contrast, at the lower latitude of Sonderstromfjord, the ice field margin is about 20 km from the seashore. Thus, local winds can drag up terrestrial dust grains that end up being deposited in the cryoconite hole, where they decrease the concentration of micrometeorites.

So, if you want to collect Greenland micrometeorites, go to Port-Victor like the boy scouts. You can use the hut that they repaired, if it has not been destroyed meanwhile by the vandalism of tourists participating to expeditions organized by a famous French tour operator and led by professional guides! In 1998 they tore out several of the wooden panels of the hut (that the kids carried on their backs in the first place) to make a fire!

Moving to Antarctica. Nevertheless, there are severe limitations of using the *melt* zone of the ice sheet as a micrometeorite collector. The biogenic activity of the bacteria heavily spoiled the relatively porous micrometeorites with organic excretions. There was no hope to investigate their carbon chemistry to tackle the difficult problem of the prebiotic chemistry of life (see Part IV). Moreover, the most friable particles were certainly destroyed during the harsh desegregation procedure that we had to apply to the cocoons hosting the dust. Finally, the particles are subjected to an ordinary aqueous alteration, as they get exposed to melted ice water for about 2–3 months each year. This process, which is repeated over centuries, leaches out soluble minerals such as carbonates and sulfates and destroys metal and sulfides.

Therefore, we moved for the first time to Antarctica in December 1987. There, the colder Antarctic summer prevents the formation of a noticeable amount of naturally melted ice water. Consequently, terrestrial weathering should be much less pronounced than in Greenland, and cryoconite should not develop. Moreover, continental wind-borne dust is much less abundant in Antarctica than around the sandy margin of the Greenland ice sheet. Indeed, this dust has to fly over 2,500 km over the oceans before reaching Antarctica, and grains with sizes $\geq 20\,\mu m$ settle in the oceans. Therefore, the concentration of terrestrial particles in the glacial sand recovered from artificially melted ice water should be much smaller, thus markedly increasing the concentration of micrometeorites –except in the smallest size fraction that we don't collect anyway.

However, as a space collector of extraterrestrial material, the Greenland ice sheet shows the unique advantage of collecting dust from huge amounts of "naturally" melted ice water. The most promising prospect is to get rid of cryoconite, looking for deep and large blue lakes, which are still forming well outside the melt zone, a few hundreds kilometers further inland, in a cold and clean area where cryoconite is not formed. Moreover, the winds, which are mostly blowing now from central Greenland, are very clean and carry only a small amount of fine-grained terrestrial dust. Consequently the glacial sand deposited on their floor should be very rich in micrometeorites. A number of very large micrometeorites with sizes of about 1 mm to 1 cm ("minimeteorites"), which are about 10,000 times less abundant than 100 µm-size micrometeorites, should be found there.

We were already thinking about exploiting such lakes with the Danes, relying on both a small inflatable rubber boat and a miniaturized version of the pumping robot used to recover micrometeorites on the bottom of the water well at the South Pole station in Antarctica (see below). Another advantage of Greenland is that the annual snow layers that accumulate in Central Greenland would be the best collector to recover micrometeorites from Leonid meteor showers with a well certified cometary origin (c.f., Sect. 22.6), due to their favorable inclination of +70° on the ecliptic plane.

Blue ice fields near Cap-Prudhomme, in Adélie land (1987, 1991, 1994, 1999). In December 1987 we set off for Antarctica, under the guidance of Michel Pourchet, a French glaciologist and mountaineer, to melt down ∼100 tons of blue ice near Cap-Prudhomme, at about 6 km as the crow flies from the French station of Dumont d'Urville. We used steam generators adjusted to deliver jets of hot melted ice water at temperatures around 70°C, to make pockets of melt ice water at a few °C with a volume of 3–5 m^3 each (Fig. 10). At the end of the day melt ice water was pumped and filtered on a stack of four stainless steel sieves with openings of ≥400 µm, 100–400 µm, 50–100 µm and 25–50 µm. This yielded glacial sand very rich in unmelted micrometeorites. We returned to Cap-Prudhomme in 1990 and 1994, to melt ∼200 tons of ice per field season, with improved collectors developed to minimize both man-made contamination and the destruction of the most *friable* grains in the pumping system. In particular all water pipes were made of the variety of stainless steel used in French nuclear reactors.

The 1999 expedition was mostly aimed at testing a duplicate of the new pump built by James Lever to recover micrometeorites deposited on the bottom of the water dwell at the South Pole, which looked like a vacuum cleaner (see below). We were hoping to find that it was less destructive than our own pumping system, thus allowing us to collect very friable SMM-type micrometeorites. But unfortunately it was not.

At the present, our Antarctic collection includes over 100,000 unmelted micrometeorites and roughly the same amount of cosmic spherules. Their host glacial sand turned to be far richer in micrometeorites than Greenland cryoconite. In the richest 50–100 µm size fraction about 20% of the particles are micrometeorites. About 80% of them are unmelted micrometeorites, which are quite easy to hand-pick for further studies (Fig. 11), and 20% are melted cosmic spherules.

Fig. 10. Recovery of a micrometeorite-rich glacial sand deposited on the bottom of pockets of melted ice water with a volume of 2–5 m^3 in the blue ice fields of Cap-Prudhomme, during our second Antarctic expedition in December 1991 (at about 6 km as the crow flies from the French station of Dumont d'Urville). Three steam generators adjusted to deliver hot water at about 70°C were used to make three pockets of melt ice water at a few °C. Each daily collection was thus recovered from a total volume of melt ice water of about 10–15 m^3, after about eight hours of operation. This water was pumped and filtered on a stack of stainless sieves. In these earlier times the plastic pipes of the pumping system, the metallic coils of the steam generators and the burning of the fuel used to heat up the water circulating in the coils generated abundant contaminants, including dark rust grains and fly ashes, both looking like micrometeorites. Later on, all pipes and coils were made of a costly variety of stainless steel very resistant to corrosion and the chimney was equipped with an efficient filter that retained all smoke particles with sizes ≥ 15 µm. Furthermore, these collects were only made when the dominant "katabatic" wind was blowing from the center of Antarctica, thus being very clear. This drastically decreased the proportion of these trouble-making contaminant particles in the glacial sand.

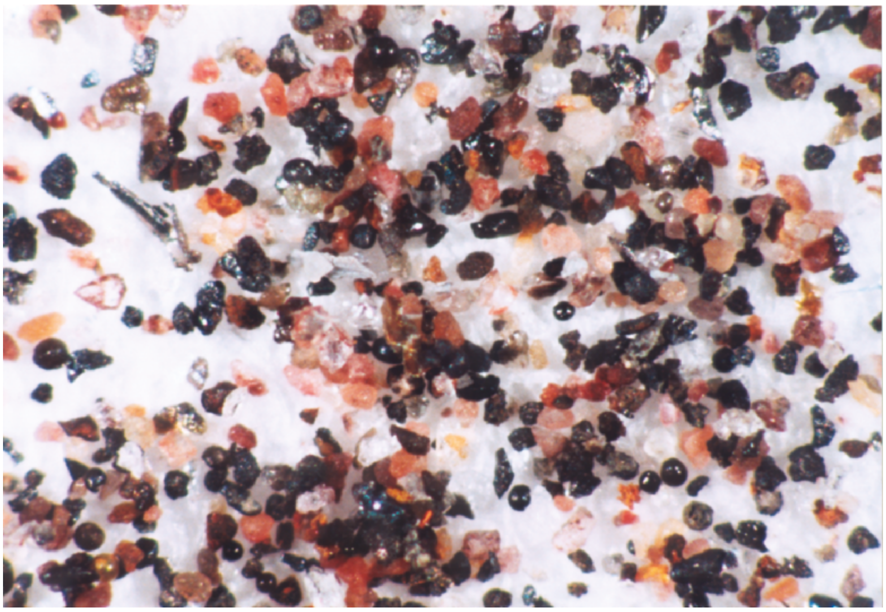

Fig. 11. This low magnification picture taken with an optical microscope represents the best size fraction (50–100 µm) of the sand collected at Cap-Prudhomme during our third and much cleaner operation in January 1994. In this size fraction one grain out of five turns at to be an unmelted micrometeorite. They appear as the dark irregular charcoal-looking particles. The spherules are just melted micrometeorites and their number is clearly smaller than that of the unmelted micrometeorites. This single shot ruined the predictions of one of the reviewers of our first proposal but also those of the models used to describe the atmospheric entry of micrometeorites, which predict a much smaller proportion of unmelted to melted micrometeorites.

A daily collection involved the making of 3 pockets of melt ice water with a total mass of around 10–15 tons, and including all particles with sizes $\geq 25\,\mu m$ typically yields about 2000 unmelted micrometeorites, 1000 cosmic spherules and 10,000 terrestrial grains with sizes $\geq 50\,\mu m$. Oddly enough, this richness is associated to an overconcentration process bearing similarities with that effective on the stagnant blue ice fields where Antarctic meteorites are accumulating. It results from a conjunction between the propagation of the solar thermal wave up to a depth of about 1 m and the exposure age of the surface of the stranding and/or dormant ice field to this solar wave. It increases the concentration of micrometeorites in the top meter of the blue ice field by a factor of about 20, with respect to the normal concentration measured at a depth of 5 m of about 10 micrometeorites with sizes $\geq 100\,\mu m$ per ton of ice.

We are pretty sure that there are blue ice fields –still to be found– where this over concentration is much higher than at Cap-Prudhomme. Indeed, the exposure age of some of the stranding ice fields on which high concentrations of Antarctic meteorites have been found can reach ∼3 Myr! However, such long exposures are not sufficient. The grains must be quickly buried, in order to be firmly anchored into the ice. Otherwise they will just be dispersed by the strong winds. We indeed observed this limitation looking at an approximately 50 kg chunk of blue ice recovered for us in 1994, by Robert Walker and Ralph Harvey, on the ∼100,000 year-old surface of a stranding blue ice field in the Queen Alexandra range, which was very rich in meteorites. The concentration of micrometeorites in the ice was quite similar to the corresponding value measured at Cap-Prudhomme (Maurette et al., 1992b).

Thus, approximately 1 ton of ices melted at Cap-Prudhomme would release as much unmelted micrometeorites (about 200) as about 20 tons of snow collected in the much colder regions of central Antarctica where the ice flow originates. In this sand, about one grain out of five is an unmelted micrometeorite. For comparison, the cleanest snow in the Alps is found near Mt Blanc, at *Dôme du Goûter*. Due to both high precipitation rates there and the lack of an overconcentration process, 1 ton of snow would yield at best about one unmelted micrometeorite, i.e., a value about 200 times smaller than at Cap-Prudhomme. Even worse, this single micrometeorite would be dispersed in a background of several tens of millions of terrestrial dust grains. In brief, it would be impossible to find a micrometeorite in such a gigantic background of terrestrial grains, including fly ashes looking like micrometeorites under a low magnification microscope, and which are very easily transported by the winds at a high elevation. Particles from the Sahara desert also like to fly to Dôme du Goûter for a visit!

American and Japanese teams started to recover and exploit *unmelted* Antarctic micrometeorites on a large scale only in 1996. Previous collection quoted by Yada et al. (2004) were mostly limited to the recovery and description of cosmic spherules. They include the first Antarctic collection recovered from snow by Nishibori and Ishizaki (1959) and the later collections recovered in the most straightforward way, just scooping moraine sand on the ice surface with an empty can –c.f., Koeberl and Hagen (1989) and Harvey and Maurette (1991).

The giant water well at the South Pole (1995, 2000). The projects of Suzan Taylor and James Lever were particularly spectacular (Taylor et al. 1998, 2001, 2003). They cleverly exploited in 1995 the water well feeding the Amundsen–Scott Station at the South Pole, which was formed by the continuous melting of about 4,000 tons of ice! There, a nice robot equipped with efficient CCD eyes, and doing an automated remote pumping at depths of about 15 meters, vacuumed up the irregular bottom of this gigantic pocket. This operation yielded a new “South Pole” collection of micrometeorites.

The first 1995 collection was spoiled by a huge underground fire which badly contaminated the AMMs. It was almost impossible to recover unmelted micrometeorites from the large amount of trash thus collected (Maurette et al., 1998). However, during their second attempt in November 2000, they made a much cleaner and valuable collection on the bottom of the same well, because the trash was removed during the first 1995 attempt. There were 13,000 cubic meters of ice melted between the 1995 and 2000 deployment!

At South Pole there is no overconcentration process to enrich the ices in micrometeorites. It could be deduced that 4000 tons of ice there is just equivalent to our 200 tons of Cap-Prudhomme ices (as multiplied by the overconcentration factor of ∼20). However, a correction should be made in this extrapolation, to account for the rate of snow accumulation at South Pole, which is about 3 times smaller than in the *formation* zone of the Cap-Prudhomme ice, about ∼500 km away from margin. With this correction, ∼200 tons of Cap-Prudhomme ices are equivalent to only ∼1300 tons of South Pole ices.

There is one limitation about this spectacular collection, which still has to be fully assessed: the pumping system used to vacuum up the dust on the bottom of the water well was still pretty destructive. In particular the proportion of fine-grained unmelted micrometeorites relatively to the harder scoriaceous-type particles was even smaller than at Cap-Prudhomme. We further tested this point by building a duplicate of the South Pole water pump thanks to the generous cooperation of James Lever, who visited our laboratory and checked the conformity of our model. We then collected micrometeorites on the same ∼100 m^2 zone of the Cap-Prudhomme blue ice field, relying alternatively on the South Pole pump and our usual pumping system. The two systems were on par to destroy the friable micrometeorites, which were subsequently discovered at Concordia through the use of a much more gentle gravitational siphoning collection system. In fact about 50% of the fine-grained AMMs found in Concordia were destroyed by both pumping systems.

The "IceCube" project at the South Pole. Lever and Taylor are now engaged in a wild cold adventure in the gigantic *IceCube* project. They have proposed to exploit 80 drill holes with a length of about 2.4 km and a diameter of about 0.6 m, which should be made with a jet of hot water at 85°C, which will shield the neutrino detectors of this ambitious project dispersed in about 1 km^3 of ice (Lever and Taylor, 2003). They rightly expect to collect about 800 micrometeorites with sizes ≥50 μm, for each ice core section corresponding to about 100 yr of accumulation (e.g., about 8 meters long). If they successfully complete this job for the 80 drill holes, they will get about 20 million micrometeorites!

We hope that this technique will be less destructive that that used at Cap-Prudhomme, and this has to be assessed, because the water circulating in the head of the drill where the micrometeorites are collected is still flowing at a speed of about 4 m per second. The huge IceCube collection would contain about 20 g of micrometeorites. It would thus allow for the first time to lend to investigators $\geq$100 mg aliquots of micrometeorites for powerful but destructive analyses, such as those performed with a (Gas Chromatograph coupled to a Mass Spectrometer) GCMS, which have already allowed the identification of about 400 distinct organics in Murchison (Cronin, 1998).

If the collection is very clean, then it will take about 30 seconds for an experienced operator to extract a promising micrometeorite-looking particle. The hand picking of the 20 g of micrometeorites in this collection would thus requires about 20 years of full time work for a single operator, an impossible task. Therefore an automated system of analysis would be built by Elmar Jessberger at the University of Munster (it is based on a laser plasma spectrometry set-up coupled to an automated optical microscope) and used to spot and chemically characterize dust particles directly on the filter on a tiny zone of a few μ^2. However, it would not be a good move to process all the filters this way. Parts of them should be saved for future generations, because sample processing biases and contaminants are always marauding in the laboratories even though some authorities declare that they don't.

Japanese collections near Dome Fuji and the Yamato mountains, Antarctica. Our Japanese colleagues also made important collections. They first recovered deposits in an approximately 200 liter water tank at their Dome Fuji station during the expedition JARE-37 (1995–1997) (Nakamura et al., 1999), which was fed with recent fallen snow around the station, and from which they hand-picked AMMs. The first collect was loaded with trash, like the first South Pole collection. However, the second collect during JARE-39 (1997–1999) was much cleaner than the first one. It allowed important analysis of AMMs, which have been used in this book.

When I visited their Institute in September 1997, a team of 13 men was getting ready to leave for Antarctica for 14 months with the major purpose of collecting meteorites on stranding blue ice fields near the Yamato Mountains. They succeeded in recovering micrometeorites at several locations during their traverse of these mountains (Yada and Kojima, 2000), melting bare ices with a ~300 liter ice smelter. The latest collects were made during JARE-41 (1999–2001) with a faster system of pumping that allowed to filter about 38 tons of melted ice water (Iwata and Imare, 2001). However, these collections are still rather similar to the Cap-Prudhomme collections with regard to cryogenic weathering of the grains and the destruction of the most friable particles (see Sect. 25.1, Subsect. 2).

5.4 Moving to Central Antarctica to Avoid "Cryogenic" Weathering

Cryogenic weathering in the top layers of blue ice fields. The Antarctic ice flow moves up to the surface after meeting some rock obstacles that also slow down its flow. It gets ablated during the short summer season and micrometeorites are thus slowly released one by one, right on the ice surface. As they are very dark, they are preferentially heated up by solar radiation and get coated with a thin film of melted ice. Then, they sink into the ice up to a depth where they freeze again. We tested several times the incredibly fast occurrence of this process during the two best months of the Antarctic summer (December and January) while throwing a handful of moraine sand on the surface of the blue ice field of Cap-Prudhomme in January 1991. These grains are rather grey than dark and they also include whitish quartz grains. However, all of them sank into the ices and disappeared in less than 30 minutes!

As the solar thermal wave penetrates up to a depth of about 1 m, they can thus accumulate at depths ranging from 25 cm up to 1 m, before being completely refrozen in the ice. As this process is effective for about 20 years on the Cap-Prudhomme ice field that we exploited since 1987, it yields an overconcentration factor of about 20.

Moreover, the thin film of water that coats them is very corrosive because the reactants products are not washed out and this leads to high pH water. In particular, iron sulfides and carbonates are quickly leached out, and this produces a highly specific depletion of S, Ca and Ni relatively to the chondritic composition of CM-type chondrites. Yada and Kojima (2000) argued that AMMs recovered from the Yamato ice fields were subjected to much less "cryogenic weathering" than those trapped in the Cap-Prudhomme ices. This conclusion is clearly invalidated by the observation that the strong depletion of S, Ca and Ni in these AMMs, relatively to the composition of CM-type chondrites (see Sect. 25.1 and Fig. 37 herein), is very similar to that observed in the Cap-Prudhomme AMMs. This marked weathering (due to a fast dissolution of soluble salts) was observed in all Japanese collections.

The unweathered "Concordia" micrometeorites collected in surface snow in central Antarctica (2000 and 2002). In sharp contrast, micrometeorites recently recovered from fresh annual snow layers buried at depths of around 4 meters in central Antarctica do not show this depletion (see Fig. 38).

These last collects were made under the leadership of Jean Duprat, in January 2000 and 2002 (Duprat et al., 2001; Duprat et al., 2003, 2004; Cuillierier et al., 2002). They are more appropriately discussed in Sect. 26.2 in the third Subsect., intitled: "*Minimizing biases with snow from central Antarctica*". Our first major objective was to find unweathered AMMs, as expected due to the much colder summer temperatures there. But we also wanted to try a new technique to recover AMMs from melted snow and /or ices, which should be much cleaner and much less destructive than any technique previously used.

For this purpose, Duprat developed a "soft" collection scheme. It involves first the melting of slabs of snow in a 200 liters all stainless steel double wall smelter heated up from the outside with hot water produced by a water heater, which was fed by a propane burner releasing a small amount of fly-ashes. Then, the pumping and sieving system used at Cap-Prudhomme was replaced by a much gentler gravitational siphoning of the bottom of the water pocket through a nylon sieve with an opening of 37 µm, driven by the opening of a tap. There is no fast flow of water throughout pipes that could crush friable particles on obstacles. We thus collected highly friable particles not previously found in Antarctica (see Sect. 16.1, 22.3, 26.1). Furthermore, the new collection did confirm that terrestrial weathering was not effective in the snow. There was no depletion of S, Ca and Ni (c.f., Fig. 37) with regard to the CM-type chondrites, and we found crystals of carbonates (calcite) and high contents of iron sulfides.

This operation taught us how to recover the best preserved and least polluted collection of Antarctic micrometeorites. In brief, we are no longer interested in beating some record for the total number of micrometeorites recovered during one field season. We prefer focusing on the quality of the collection, which should be very clean, subjected to a minimum amount of weathering (it would just be related to their exposure to melt snow water at a few °C for about 8 hours) and recovered from the ice in the least destructive way.

6 Classification of Meteorites and Micrometeorites

Archeologists only started to trace back successfully the advance of the Roman legions, trade patterns and the evolution of manufacturing techniques in Roman time, once they found an efficient scheme of classification for the fragments of amphora used to transport wine for the soldiers. Similarly, the classification of meteorites and micrometeorites is an essential step in the exploitation of these extraterrestrial debris. We recall that one of the main objectives of meteoriticists over the last 30 years was to find the most primitive objects of the solar system, which have been the least reprocessed since the formation of the early solar nebula, with the view to exploit them as reliable archivist of our distant past. This section outlines some of the methods used to classify meteorites and Antarctic micrometeorites. It also summarizes some of the key features of the surprisingly simple relationship between micrometeorites and a relatively rare group of stony meteorites, the hydrous–carbonaceous CM-type chondrites, which was only confirmed recently after the study of the Concordia micrometeorites collected in central Antarctica in January 2002. A more technical discussion of this relationship presented in Sect. 25 will allow its extension to the smaller micrometeorites collected by NASA in the stratosphere. The book of Wasson (1985) is still one of the best monographs about meteorites.

6.1 Meteorites

From mineralogy and petrography to isotopes. Since the pioneering work of Chladi (1799), the identification of the extraterrestrial origin of meteorites and their classification has been performed by several generations of scientists. They first used classical methods developed in the fields of mineralogy and petrography to both identify the extraterrestrial origin of a rock and characterize its mineral assemblage with the view of understanding its formation (Fig. 12).

For example, a major silicate such as olivine, which is abundant in primitive meteorites, might contain 200 times more chromium than terrestrial olivine. These concentrations can be easily measured with an analytical electron microscope and they already give a good criterion to identify the extraterrestrial origin of a rock. It was already found with these classical

M. Maurette, Classification of Meteorites and Micrometeorites. In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 54–71 (2006)
DOI: 10.1007/10911310_6

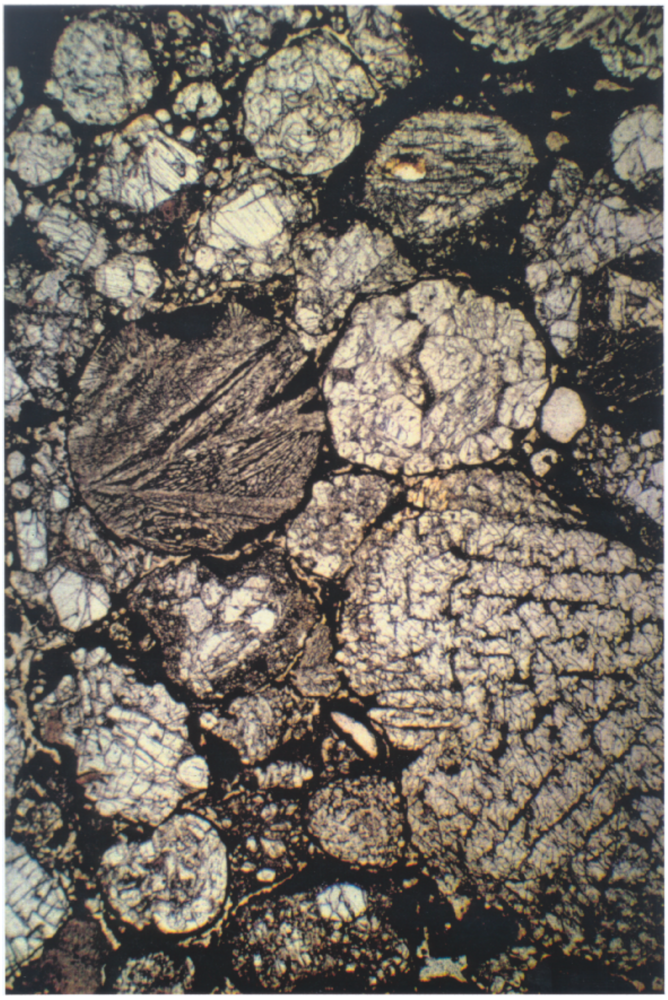

Fig. 12. A well-trained mineralogist can quickly identify the extraterrestrial origin of a stone found in a desert, just looking at its dark varnish (Fig. 3) and at a fresh internal fracture surface with a simple magnifying glass. The second step consists of observing a thin section of the rock with a petrographic optical microscope in the laboratory. This micrograph represents the ordinary chondrite Tieschitz observed in transmitted light with the optical microscope (the length of the field of view is about 5 mm). About 80% of the mass of the meteorite is made of rounded objects with sharp edges called chondrules. The space between chondrules is fillep up with angular minerals and glass, whereas the dark material is the fine-grained matrix. This observation of chondrules is sufficient to identify the extraterrestrial origin of about 80% of the meteorites, because terrestrial rocks do not contain chondrules. The high abundance of chondrules in this meteorite reflects the existence of a still mysterious chondrule "factory" in the early solar nebula. These standard optical microscope observations are followed by an accurate chemical analysis of the constituent minerals of the meteorite with an analytical electron microscope (Courtesy of G. Kurat).

methods that there are three broad groups of meteorites, including stony, iron and stony–iron meteorites. The stony meteorites are essentially composed of silicates while the iron and the stony–iron are mostly made of large single crystals of two alloys of Fe and Ni (coined FeNi–metal) and a mixture of FeNi–metal with numerous silicate inclusions, respectively. If one focuses on the world collection of about 1000 meteorites that were collected soon after their fall, and which are quoted as "falls", about 94%, 5% and 1% of them are stony, iron and stony–iron meteorites, respectively.

Subsequently, powerful techniques of isotope geochemistry were developed to improve this earlier classification, such as that proposed in 1973 by Clayton and collaborators (c.f., Clayton, 1993). It makes use of the oxygen isotopic composition of all types of meteorites, which is displayed conveniently on a 3-isotope scatter plot, giving the variations of the $^{18}O/^{16}O$ ratio as a function of the $^{17}O/^{16}O$ ratio. Major groups of meteorites occupy clusters of points on this plot that some interpret to indicate that they have formed in different reservoirs of oxygen in the early nebula. These differences in oxygen isotopic composition correspond to other differences in chemical composition, bearing for example on moderately volatile lithophile (Mn, Na and K) and siderophile (Ga, Sb, Se, Zn) elements, which have the chemical tendency to concentrate in the silicates and in the metal phases, respectively.

Moreover, mineralogists who characterize the assemblage of minerals that make a "rock" divide most groups of meteorites into seven additional metamorphic subgroups, which thus complete the isotopic, chemical and mineralogical classification. They refer to the degree of heat metamorphism and to the extent of aqueous alteration suffered by the meteorite parent bodies over a long time scale (~1 Myr). Heating at moderate temperatures ($\leq$800°C) never triggered the melting of these bodies. But it activated a redistribution of the constituent atoms of the different mineral phases by diffusion in the solid state. Furthermore, it led to the loss of constituent volatiles, such as water, and to a destruction of their organics.

One of the simplest methods to track the thermal history of chondrites is to define their metamorphic grade relying on a polished section to look at the sharpness of the edge of chondrules imbedded into their fine grained host matrix (see Fig. 12) –all chondrites, except those of the CI group, contain these rounded objects. This sharpness progressively vanishes as the recrystallization of the host matrix and chondrules blurs it. In groups 1 to 3 these edges are very sharp. However, in grade 7, chondrules cannot be distinguished anymore from the matrix, where the mineral assemblage has become equilibrated –e.g., the Fe/Si ratio of all olivine crystals are now similar, and the composition of another silicate such as pyroxene can be predicted from that of olivine by applying the laws of crystal chemistry. Each one of these major chondrite groups is thus divided into many subgroups.

The final classification of meteorites is summarized in Fig. 13 where only the major groups have been reported. It shows:

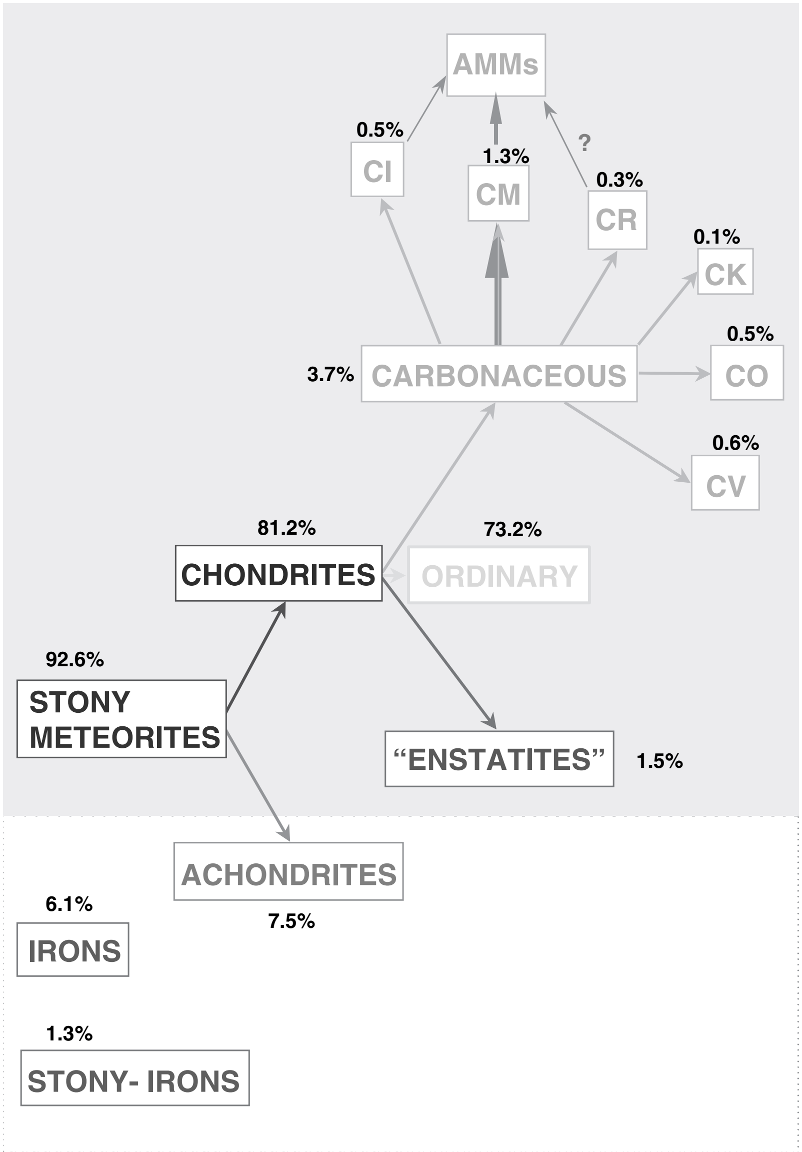

Fig. 13. This is the conventional classification of meteorites displayed here to illustrate their relationships with Antarctic micrometeorites (AMMs). The "differentiated" meteorites found in the red bottom part of the plot have been formed during the cooling of magma (i.e., they are igneous rocks). In sharp contrast, the constituent grains of meteorites found above this zone have never been melted since their formation in the solar nebula. The approximately 2500 Antarctic micrometeorites investigated in our work are essentially made of a material related to the CM-type chondrites and only a few ones can be related to the differentiated meteorites (Courtesy C. Engrand).

– 5 major groups of chondrites, including the carbonaceous chondrites (see below) and the H-, L-, LL- and E- chondrites;
– 6 major groups of achondrites (Howardites, Eucrites, Diogenites, Aubrites, Ureilites and SNC meteorites);
– two major groups of stony iron meteorites (Pallasites and Mesodiderites), and;
– three major groups of iron meteorites (Octahedrites, Hexahedrites, Ataxites).

We only briefly quote the groups of the stony–iron and iron meteorites, which represent about 1% and 5% of the meteorite falls, respectively, because we did not find iron and/or stony–iron objects in a set of about 2500 Antarctic micrometeorites. Iron meteorites show a simple mineralogical classification with three major groups. However, the measurements of their iridium and nickel contents reveal more than 100 distinct subgroups, which cannot be derived from each other by any known processes, such as melting and solid state diffusion. Furthermore, their silicate inclusions illustrate what Gero Kurat has coined *mineralogical chaos* in meteorites (see Sect. 6.4).

Chondrites and achondrites. In this classification, the stony meteorites, which are by far the most abundant objects, are divided into two fundamentally different groups of rocks, the chondrites, which contain up to 80% of chondrules, and achondrites, where chondrules are not observed. Their differences to chondrites are farther reaching than the lack of chondrules. In fact they are differentiated rocks resulting from the cooling of a melt. They are much less primitive than chondrites but still very interesting. Some chondrites and achondrites are "gas-rich". They contain in particular high concentrations of solar neon, because they are breccias formed upon impact compaction of the regolith of their parent asteroids (see Sect. 3.4).

The most abundant group of the chondrites (about 86 % of the meteorite falls) show a high abundance of chondrules, which represents about 20 to 80% of the meteorite mass, and which have no equivalent on Earth –they can be defined as spheroidal particles with sizes of about 1 mm, which were once formed by partial or complete melting and quenching prior to incorporation in meteorites (see Fig. 12). The remaining mass is made of a heteroclite assemblage of distinct components formed at different times and different zones of the solar nebula (see details about this "chaotic" assemblage in Sect. 6.4).

The achondrites (about 8 % of the falls) are very different rocks that acquired some fame because they include rocks originating from the Moon and, possibly, from Mars and the second largest asteroid, Vesta. They are differentiated igneous rocks, which solidified from magma, and bear similarities with terrestrial oceanic basalts. They do not contain chondrules and CAIs.

6.2 The Hunt for "Primitiveness"

In our work we only use stony meteorites. These stones can be classified on a scale of "primitiveness". Only about 4 % of the meteorites show simultaneously highly unequilibrated mineral assemblages, high contents of volatiles, and chondrules with sharp edges. They constitute the group of the most primitive "carbonaceous" chondrites of metamorphic classes 1, 2 and 3. They have been classified in seven major subgroups, CI, CM, CR, CO, CV, CK and CH. Moreover, several ungrouped carbonaceous chondrites, such as "Tagish Lake", which fell in Canada in 2001, do not fit into the established groups.

The CI-, CM- and CR-type chondrites are made of a dominant hydrous–carbonaceous material and they will be called HCCs in this book. They are generally considered to be the most primitive meteorites (Fig. 14, top). In particular, their mineral assemblage is highly unequilibrated with regard to that observed in metamorphic classes 4 to 7. Indeed, they still contain mineral phases that discompose quickly within a few days at low temperatures of about 500–600 °C in the laboratory and such as serpentine (a hydrous silicate) and carbonates. The dominant hydrous silicates of AMMs is saponite which starts dehydrating at ∼100 °C. These phases coexist with the most refractory phases, called Calcium–Aluminum-rich inclusions (CAIs), made of mixture of refractory oxides of aluminum and calcium, which can only be formed at temperatures ≥1500 °C, e.g., close to the early Sun.

They are the most water rich meteorites. Water, which is stored as OH (structural water) and H_2O in their hydrous minerals, reaches concentrations of about 20%, 8% and 5% in the CI-, CM- and CR-type chondrites, respectively. They are also the most carbon- and nitrogen-rich meteorites. In the CI- and CM- subgroups these two biogenic elements are mostly associated with a dominant carbonaceous component made of kerogen, yielding a carbon content varying from ∼1 to ∼ 5 wt.%. These rare chondrites, rich in kerogen and water, also contain smaller amounts of complex and reactive organics such as amino acids at concentrations levels up to ∼0.01%, which have attracted much attention in exobiology since their discovery (Orò, 1961). About 400 distinct organics have already been found in Murchison (a CM-type HCC) and up to several thousand organics might be potentially found (Cronin, 1998). They are found in a carbonaceous component, which is soluble in organic solvents (and can thus be extracted), contrarily to kerogen, which is one of the most insoluble extraterrestrial materials (see Sect. 16.2). This soluble component amounts to about 10% of the total organic carbon.

In contrast, the fine-grained matrix of the other groups of carbonaceous chondrites (CO, CV, CK, CH) is much drier (Fig. 13, bottom). They contain a few hydrous minerals and the majority of these carry water as OH-group in their structure (i.e., amphiboles). They also lack amino acids, which are apparently associated with high water contents. But they show the largest CAIs with sizes of up to 1 cm.

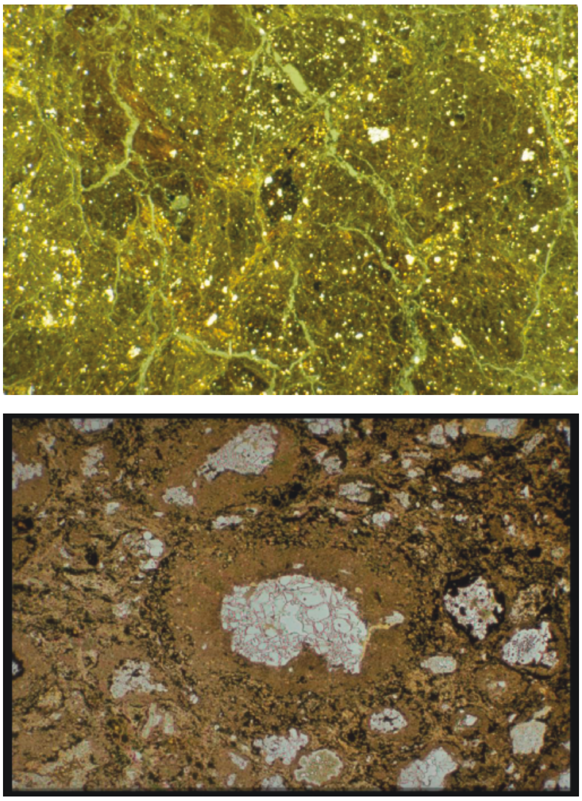

Fig. 14. Transmitted light images of thin sections of the Orgueil (top) and Banten (bottom) chondrites that belong to the CI- and CM-type carbonaceous chondrites, respectively (length of the field of view: 5 mm, top; 1 mm, bottom). They represent two end members of the group of carbonaceous chondrites. About 99% of the Antarctic micrometeorites are related to these relatively rare meteorites. Orgueil is essentially made of hydrous silicates containing a carbonaceous component of kerogen. The CI- and CM-type chondrites contain the highest contents of water bounded to their hydrous silicates (about 20 and 8%, respectively). In Orgueil, the rare black grains are crystals of magnetite and sulfides, which are opaque to transmitted light and the white veins, are micro-fractures partially filled-up with magnesium sulfates –they were probably formed during the weathering of the meteorite during its exposure to atmospheric moisture. The chemical composition of the CI-type chondrites shows the closest fit with that of the solar atmosphere considered to be a chunk of the early solar nebula. Next, the CM-type chondrites are the closest to this primitive CI chemical composition. The central bright grain with a size of about 200 µm in Banten is an aggregate of olivine crystals that apparently accreted a thick mantle of dust, and which was called a "mud ball" by Kurat. Such mud balls might well represent the earliest stage of accretion in the solar nebula. The olivines of the central aggregate are considered to be refractory phases that formed at temperatures of around 1500 K in the early solar nebula (Courtesy G. Kurat).

Next in primitiveness one finds the most populated group of the "ordinary" chondrites. They are exclusively found in metamorphic groups 3 to 7. They contain much less volatiles (such as C, N, S and water), the edges of their chondrules are in general less sharp, and starting at metamorphic grade 3 their mineral assemblage begins to equilibrate.

About 8% of the meteorites belong to the group of the stony achondrites made of chunks of igneous rocks, which thus lost their "primitiveness" upon melting. They include the two major groups of HED and SNC meteorites. They have acquired some fame because they include about 39 lunar meteorites and about 30 meteorites presumed to originate from Mars. Moreover, HEDs show two important characteristics that were not expected at first in melted rocks, and which turned to be quite helpful in our work. They are:

– microclasts of foreign material with sizes of about 200 µm, which are indeed "fossil" juvenile hydrous–carbonaceous micrometeorites formed prior to about 4.2 Gyr (see Sect. 10.1);
– a component of "gas-rich" grains containing solar neon implanted during the top surface exposure of the grains in their parent asteroidal regolith, prior to their compaction into a meteoritic breccia (see Sects. 3.4 and 19.2).

An important feature of many stony meteorites extensively used in our work is that they are brecciated rocks like the most abundant "breccias" collected on the lunar surface. These breccias are formed upon the shock-induced compaction and sintering of the few meters-thick loose layer of fine-grained debris that tops their parent bodies. This applies to the 39 lunar meteorites that are all regolith breccias except 5 cm-sized fragments of igneous rock. Oddly enough all the approximately 30 Martian meteorites are igneous rocks. None of them is a breccia and we still have trouble understanding this unique feature in terms of a Martian origin, as most of the Martian surface is covered by megaregoliths like the Moon.

6.3 The "Deceptively" Simple Classification of Antarctic Micrometeorites

Early expectations about an extended cosmic raking of the interplanetary medium. About 15 years ago, when Mireille Christophe-Michel-Levy, Gero Kurat and Robert Walker joined our investigations, we were all enthusiastic about the prospect of finding new objects not yet represented in the meteorite collections.

Indeed, as a result of their small sizes, micrometeorites have orbits that can be perturbed not only by gravitational forces due to the planets and the Sun, but also by a variety of non gravitational forces related to their illumination by solar radiation. Consequently, with the assistance of these additional forces, it is easier for such small objects to reach Earth crossing orbits, because their orbit rapidly spirals to the Sun. A fraction of the dust particles generated by comets and asteroids can evolve towards such orbits. In this way, a fraction of the particles generated by comets and asteroids can cross the orbit of the Earth. In contrast, only gravitational forces can perturb the orbits of the much larger meteorites, mostly ranging in sizes from fist to head. Only a very small and non representative fraction of them can evolve into an Earth-crossing orbit (see Sect. 1, Subsect. 6).

As pointed out by Liou et al. (1999), "interplanetary dust particles therefore occupy, and sweep through, more interplanetary space than do the rest of the solar system bodies. They are found from near the Sun (the F-corona) to at least 18 AU away from the Sun (Pioneer 10 measurements)". In brief, with interplanetary dust particles captured by the Earth as micrometeorites one hopes to perform a much wider "cosmic raking" of the dominant material existing in the interplanetary medium, which should yield brand new objects, not represented as yet in the meteorite collection. But to identify such oddities we first had to get familiar with the major groups of meteorites.

To look for such objects, about 2500 Antarctic micrometeorites from the Cap-Prudhomme collection (CP-AMMs) have been individually investigated by a consortium of scientists mostly including M. Christophe, E. Delousle, J. Duprat, C. Engrand, M. Gounelle, C. Hammer, G. Kurat, G. Matrajt, M. Maurette, M. Perreau and C. Olinger –see Maurette et al., 1991; Kurat et al. 1994; Engrand and Maurette 1998; Maurette et al. 2000; Gounelle 2000; Matrajt 2001; Maurette et al., 2001; Matrajt, 2002; Duprat et al. 2003). Subsequently, our Japanese colleagues organized a consortium of 13 laboratories to investigate a similar number of Antarctic micrometeorites from their own collections.

A textural classification. Genge et al. (2005) claim that the mineralogical and chemical properties of AMMs cannot be representative of their parent bodies even on a cm-size scale. This is true if the parent bodies of micrometeorites are asteroids. But this is irrelevant if the parent bodies of micrometeorites are just cometary ices and/or snow balls. In this case, micrometeorites collected in Antartica represent a random selection of particles ejected from the inner solar system and that sprayed the formation zones of cometary ices (see Sect. 24.1). And lately, they were further mixed in the zodiacal cloud before striking the Earth. One can just question whether a sampling of about 100 AMMs from the Concordia snow is enough to characterize this random mixture of cometary dust grains. What is the meaning of a cm-size sampling of the zodiacal cloud any way? For this reasons, we just kept in these book the simplest textural classification inferred in earlier times with the help of Gero Kurat. This classification was first inferred from their extent of frictional heating upon aerodynamical braking in the thermosphere. It is illustrated in Fig. 15 for the best glacial sand collected at Cap-Prudhomme in the 50–100 μm size fraction, where about 20% of the particles are micrometeorites.

Micrometeorites can be classified in four major textural classes, including:

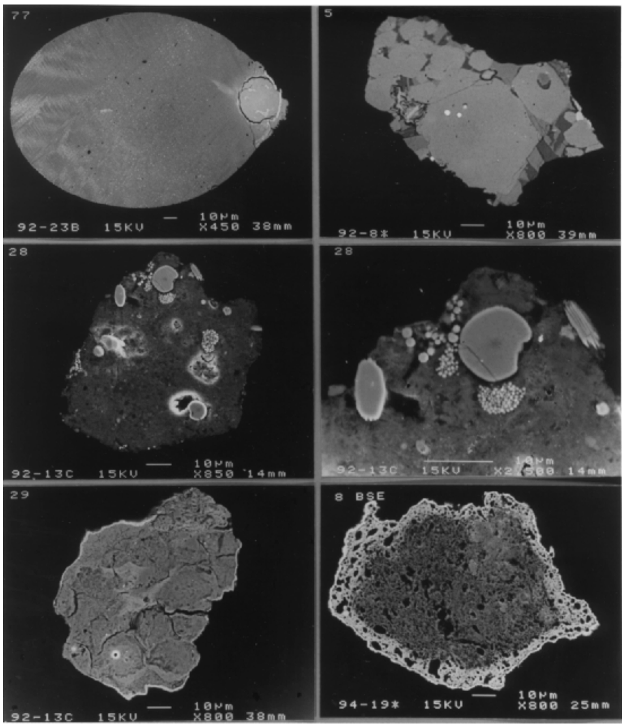

Fig. 15. Textural classification of Antarctic micrometeorites collected at Cap-Prudhomme. The new Concordia collection contains an abundant type of highly friable micrometeorites not reported here (see Fig. 35). This classification is defined from the observation of a polished section with a scanning electron microscope, which might just include a fragment of the micrometeorite (the white scale bar given below each micrograph corresponds to 10 μm). The micrographs are identified with a number in the upper left corner: **(77)** Melted micrometeorite coined as cosmic spherule, showing a nugget of ferrihydrite protruding on the right hand side (see also Fig. 31); **(5)** Crystalline micrometeorite made of a few single crystals of pyroxene and olivine containing bright metallic nodules: **(28)** the left and right micrographs refer to a relatively rare type of CP-AMMs related to CI-type chondrites. They show the typical aggregates of magnetite crystals, which characterize this type of meteorite and that appear either as "platelets" (upper right side on right) or "framboids"; **(29)** the most abundant type of fine-grained micrometeorites related to the CM-type chondrites; **(8)** a scoriaceous-type micrometeorite that was initially a fine-grained micrometeorite, which was more strongly heated up upon atmospheric entry. This produced a partial dehydration of the hydrous silicates, leading to the formation of a rind of vesicles, which start invading the particle from the outside. The much thinner approximately 1 μm thick bright rim that surrounds most micrometeorites –except when they have been purposely fragmented into several pieces like particle **(5)**– corresponds to a thin shell of magnetite formed upon atmospheric entry, and which is more appropriately discussed in Sect. 13.2 (Courtesy C. Engrand).

- *Fine-grained unmelted micrometeorites* (micrographs 28 and 29). These Fg–AMMs, represent about 35 % of the AMMs. They have been the least heated up and are made of a highly unequilibrated assemblage of minerals composed of millions of very tiny grains, in which larger inclusions with sizes of up 30 µm are included. In this assemblage hydrous minerals such as saponite, which discompose at low temperatures (100–200 °C), coexist with CAIs, which are similar –except for their much smaller sizes– to those observed in HCCs with regard to their oxygen isotopic composition. The bright tiny magnetite framboids observed in particle 28 clearly relates it to the CI-type chondrites, where they have only been previously observed;
- *Crystalline unmelted AMMs* (Micrograph 5). They are unmelted micrometeorites that represent about 10 % of the AMMs. They are composed of a few single crystals of anhydrous silicates (pyroxene and olivine in about the same abundance).
- *Scoriaceous-type AMMs.* (micrograph 8). The abundance of these Sc–AMMs is similar to that of the Fg–AMMs (∼30%). They show abundant vesicles. They were initially Fg–AMMs, which suffered a stronger frictional heating leading to a loss of volatiles, such as organics and water, and to a partial melting of hydrous minerals (Kurat et al., 1994). However, the investigation of the Concordia Sc–AMMs showed that their anhydrous silicates and most of their sulfides have been preserved. Moreover, they still contain high concentrations of solar neon. One can clearly observe both a thin bright magnetite rim around the particle that clearly decorates its atmospheric entry and a thicker rind of vesicles;
- *Cosmic spherules* (micrograph 77). They are micrometeorites that were fully melted upon atmospheric entry and not ablation products of larger meteorites. This was shown about 15 years ago, when Raisbeck and Yiou (1987, 1988) found that the ^{10}Be content of individual large cosmic spherules (sizes ≥400 µm) from both Greenland and Antarctica was similar to that measured in an aliquot of 24 unmelted Antarctic micrometeorites with sizes of around 200 µm. Furthermore, the ratio of cosmic spherules to unmelted micrometeorites increases with their sizes as expected upon the frictional heating of an incoming flux of small objects. In the 50–100 µm size fraction they represent about 20 % of the AMMs. However, in the ≥100 µm size fraction, where AMMs get more strongly heated up upon atmospheric entry, this proportion increases to about 50 %. The bright nugget on the right hand side, still coated with the typical thin magnetite rim, is made of ferrihydrite. The origin of these nuggets, which show very different shapes, is further discussed in Sect. 13.3 (see also Fig. 31).

A surprisingly simple relationship with CM-type chondrites. The measurements of their mineralogical, chemical and isotopic compositions reveal that the classification of micrometeorites is astonishingly simple. About 99% of them are only related to the CI- and CM-type subgroups of the primitive volatile-rich chondrites, and 95% of them to the CM chondrites.

Out of about 2500 AMMs we did not find any micrometeorites made of FeNi metal and Gounelle et al. (2005) only found a few rare AMMs related to achondrites. These hydrous–carbonaceous objects can release water and other volatile species, such as noble gases, N_2, CO_2, CO, SO_2 and Cl_2, during their volatilization and/or degassing upon atmospheric entry –the other carbonaceous chondrites (CR, CH, CO, and CV) release smaller amounts of volatiles.

This surprisingly simple relationship is more appropriately discussed in Sect. 25, where the chemical composition of the Concordia micrometeorites is compared to that of the CI- and CM-type chondrites. But it is also clearly imprinted in the micromappings of the C and N concentrations reported by Matrajt et al. (2001b) for both Cap-Prudhomme AMMs (Fig. 16) and $\sim$100 µm-sized tiny fragments of Murchison, a CM-type chondrite constantly used as a reference sample in our work. Multiple fragments of Murchison amounting to about 100 kg of material were recovered soon after their fall in Australia. This large mass makes it easier to request and get a small internal chunk of the meteorites that was well shielded from terrestrial contamination. It also allowed many different studies of this meteorite, which has been in particular the best investigated in the field of carbon geochemistry.

In both AMMs and Murchison a close association of C and N on a microscale of a few micrometers is always observed. This demonstrates the existence of a major carbonaceous component, which is rather similar in both types of carbonaceous materials, as indicated by its average C/N ratio of about 25–50. Such values are typical of a class of material called kerogen. This dominant kerogen has already been identified in HCCs by conventional techniques of carbon geochemistry on large aliquots of material (e.g., a few hundred mg) treated with a complex etching protocol involving both strong acids and organic solvents (Cronin, 1998). This protocol allows considerably increasing the content of kerogen in this acid resistant residue, which typically represents a few % of the initial mass of material. In brief, kerogen is one of the most insoluble extraterrestrial materials known at this date. The properties of this inert material are also exploited in both the prebiotic chemistry of life (Sect. 16.2) and the search for star dust in meteorites (Sect. 28).

These high contents of C and N stored as a carbonaceous component constitute a unique signature of the hydrous–carbonaceous chondrites. Indeed, all other meteorites, including the ordinary chondrites, are strongly depleted in both elements by a factor $\geq$10. The work of Matrajt et al. (2001b) is almost self-sufficient to illustrate the surprisingly simple relationship between micrometeorites and the HCCs.

A deceptively simple classification? When we got these first hints about this simple classification of micrometeorites, we were at first disappointed. For sure, they were not just an ordinary mixture of fragments of the numerous groups of meteorites. On the other hand, we did not fulfill our initial objective to discover new objects not yet found in the meteorite collections.

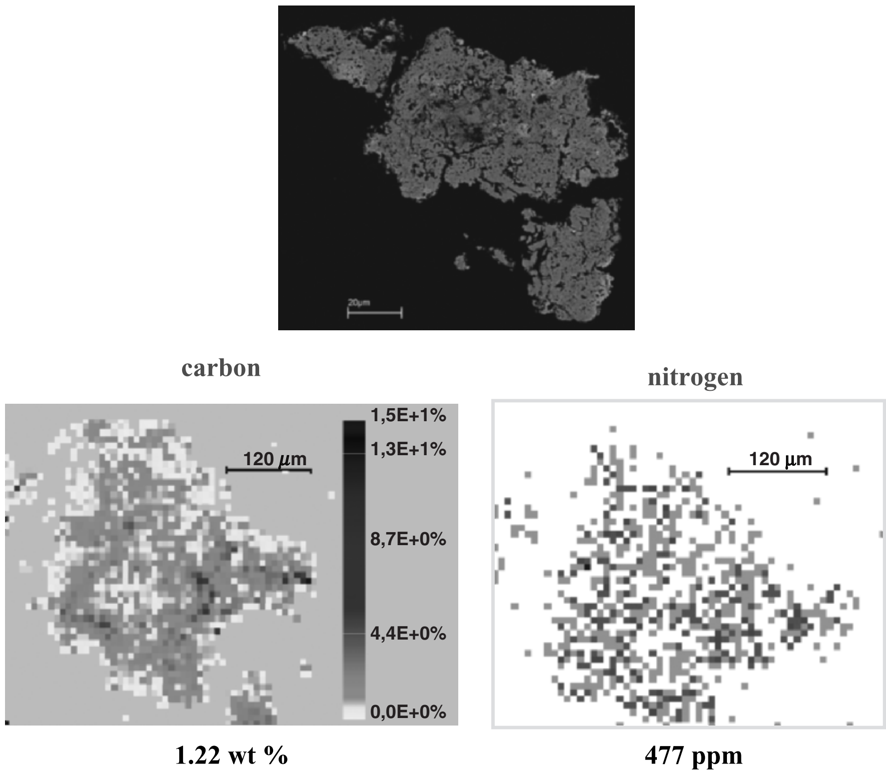

Fig. 16. A beam of deuterons was used in a nuclear microprobe to get the micromappings of the carbon and nitrogen concentration in ∼200 µm size fragment of a fine-grained Antarctica micrometeorite collected at Cap-Prudhomme (the particle was crushed on a gold foil in ultra-clean conditions to minimize C and N contaminations). The resonant nuclear reactions used in this instrument –such as ^{14}N (d,p) ^{15}N for the measurement of the nitrogen content, which is very difficult to get with other microprobe techniques– present the unique advantage of reducing nitrogen and carbon contaminations. Indeed, the electronics of detection of the nuclear reaction products allow to reject the most energetic ones emitted from the top approximately 1µm-thick layer of the grains, which is always contaminated. The technique is thus quite powerful for getting a meaningful micromapping of the C and N contents, which shows that the contents of C and N are clearly correlated. This technique yields in particular the values of the C and N contents as averaged over the whole surface as well as the value of the C/N ratio on many spots of a given particle. The micrograph corresponding to a scoriaceous type AMMs is given in Fig. 21 of Sect. 9.1 (Courtesy of J. Gallien and G. Matrajt).

But this deception slowly turned to excitement, when we gradually realized the hidden importance of observations supporting the following deductions:

- in spite of similarities AMMs show differences with the CM-type chondrites, indicating that their parent bodies are new objects, not found as yet in the family of asteroids sampled in the collection of meteorites (see a summary of these differences in Sect. 25.4);
- there is an amazingly good similarity between the isotopic and chemical compositions of volatile species (Ne, N_2, H_2O, CO_2) observed in AMMs, recovered from $\leq$50,000 years-old Antarctic ices, and the early Earth's atmosphere, which was formed about 4.4 Gyr ago;
- the $^{20}Ne/^{22}Ne$ "solar" ratios (about 11.8–11.9) observed in micrometeorites, the atmosphere of Venus and about 60 % of a variety of rocks (Mid ocean ridge basalts) from the upper mantle, are unexpectedly similar (c.f., Sect. 19.5).

In fact, the enlarged cosmic raking of micrometeorites in the interplanetary medium now reveals that the dominant material of the interplanetary medium is mostly related to the CM-type chondrites, which represent only about 2.5% of the meteorite falls. This material is different from the mixture of debris expected from interasteroidal collisions, and which are sampled in the meteorite collections dominated by the "dry" chondrites. We are left with the initial prospect that AMMs might originate from the other type of abundant dust producing bodies existing in the solar system, i.e., comets (c.f., Sect. 22). In this case, one faces the new problem of understanding why cometary dust has such a simple composition.

6.4 Beware of Chemical, Mineralogical and Isotopic "Chaos"

This section summarizes the mineralogical, chemical and isotopic "chaos" observed in the world of meteorites, and which is described in the book of Kurat and Maurette (1997). Here, "chaos" means something highly variable and unpredictable, which does not fit conventional views.

Kurat pointed out a memorable chaos in the chemical and mineralogical compositions of the three major groups of iron meteorites, which present the simplest mineralogical composition. Indeed, they are made of huge single crystals of two alloys of iron and nickel ("FeNi–metal") that can reach sizes of about 1 meter (Fig. 17). Let us just consider the bulk concentrations of two siderophile elements, iridium and nickel, measured on a large volume of FeNi–metal, and which yield the "scatter" plot reported in Fig. 18. About 700 iron meteorites have been analyzed to date. On this diagram each dot represents the bulk analysis of one meteorite. The data points form about

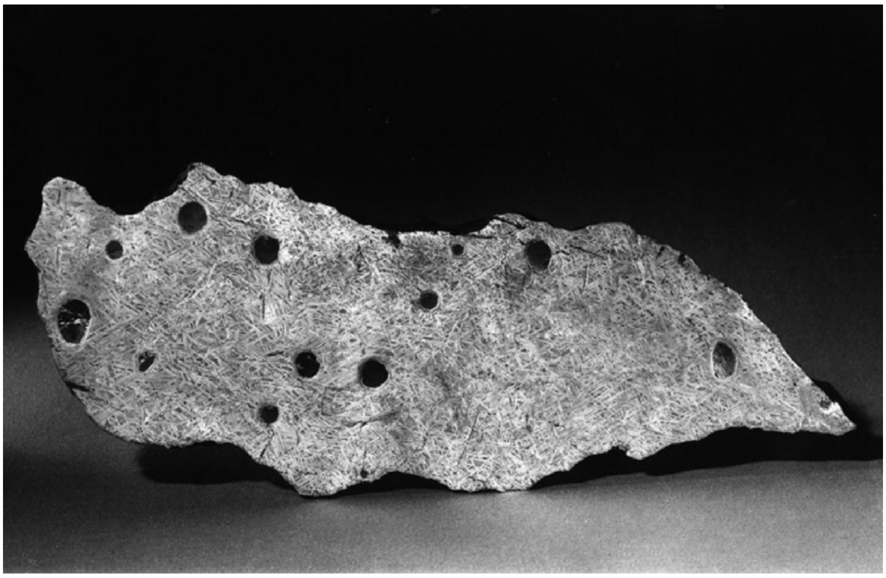

Fig. 17. Photograph of the polished section of the Mt. Edith iron meteorite (an octahedrite) from the Austrian collection of meteorites in Vienna. This section is about 20 cm long. The Widmanstätten pattern of parallel bars was revealed by a slight etching with dilute nitric acid. It has been interpreted as showing that the meteorite was a former single crystal of iron (gamma) that broke down into alpha plus gamma iron upon cooling below 900°C (Courtesy G. Kurat).

13 clusters (which can be spotted by trained eyes) that each defines a major chemical family of iron meteorites. However, about 25% of the data are well outside these clusters, and they cannot be linked to the corresponding family defined by the clusters. Consequently, it can be argued that this plot shows that in the iron meteorite collection no two objects are similar! This group alone, which represents only 5% of the meteorite falls, would already involve several hundred parent bodies!

Chaos in mineral composition can be illustrated with the same iron meteorites. A close look at polished sections reveals tiny inclusions of silicates with sizes around 100 μm, embedded in large host single crystals of FeNi metal, which might reach sizes of 1 m! Some of the inclusions form larger fluffy aggregates with sizes of up to 1 mm (Fig. 19). They show the chondritic composition of primitive chondrites and high contents of solar neon.

This is a fantastic chaos leading to odd conclusions about the formation of iron meteorites. Indeed, the presence of solar neon in such delicate aggregates requires that their constituent grains have been first individually exposed to solar radiation with a low penetration in solids ($\leq 100\,\mu m$), before being trapped in the mass of iron. Furthermore, they should not have been heated

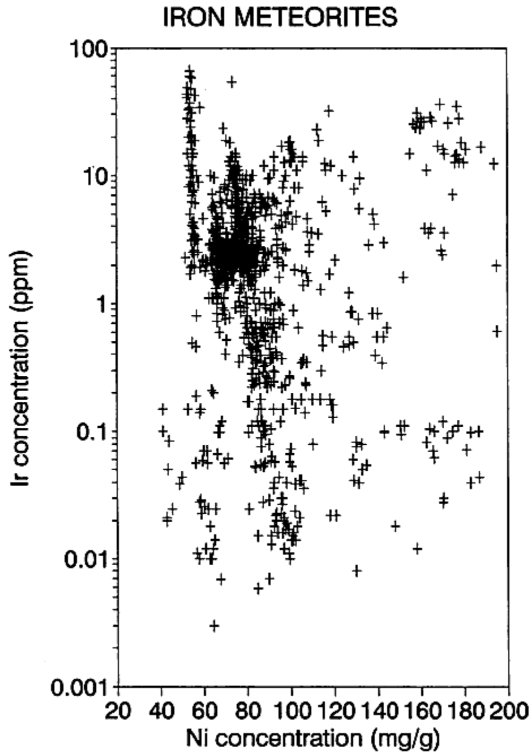

Fig. 18. Scatter plots of the concentration of Ir and Ni in about 700 iron meteorites. Each data point represents a meteorite. The wide dispersion of the data supports the surprising deduction that iron meteorites, which represent about 6% of the meteorite falls, have more than 100 distinct parent bodies (Courtesy G. Kurat).

up above about 500 °C for any extended period of time in order to retain this solar neon.

This runs against the current paradigm that the parent bodies of iron meteorites have been thoroughly melted and slowly cooled in order to generate an iron core. In this case, such delicate gas-rich stony aggregates should not have been preserved. Consequently, Kurat argues that iron meteorites are just huge single crystals that get slowly formed by the classical process of vapor phase deposition in the early solar nebula. Iron meteorites could have thus trapped their fluffy inclusions of silicates during their gentle low temperature crystal growth. In this case, they should be as primitive as hydrous–carbonaceous chondrites! This is quite of a stunning deduction, which certainly greatly irritates conventional wisdom. Nevertheless, it cannot be rejected, yet. Beware! In this world of chaos other alternatives should be considered. Zolensky pointed out that these inclusions might have been formed during the destruction of their host FeNi parent core. Then they could

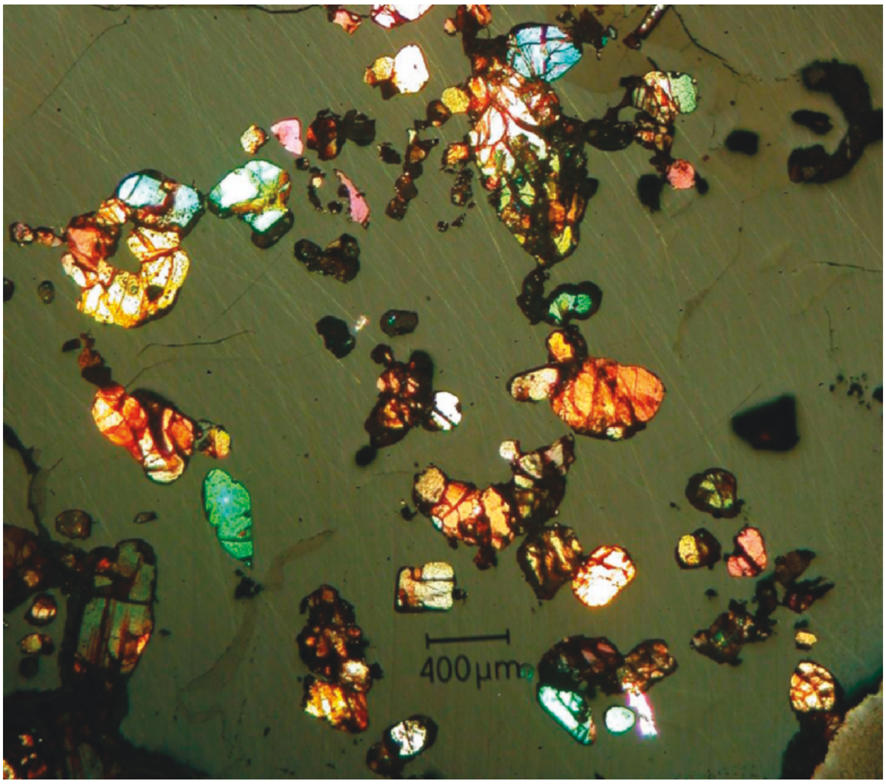

Fig. 19. Cross polarized reflected light image of a polished section of the Udei Station iron meteorite (length of the picture 0.8 mm), which show beautiful aggregates of silicate grains that are fixed in the metal. These grains show a high content of solar neon initially present in the solar nebula, which should have been lost at the high temperature required to melt a huge mass of FeNi in the first place. Moreover, the very delicate structure of these aggregates should have also been destroyed very quickly if they were in contact with liquid metal. This is a fine example of the mineralogical "chaos" defined by G. Kurat. The bright colors originate from interferences in polarized light (Courtesy G. Kurat).

be individually exposed to the solar wind and re-accreted subsequently into a "rubble-pile" FeNi type asteroid.

The CI chondrites illustrate amazingly well that mineralogical chaos also exists within the group of the most primitive meteorites. Their chemical composition is the most primitive of all, because it is the closest to the composition of the solar atmosphere (deduced from photospheric lines), which is considered to be a remnant of the solar nebula (see Sect. 25.1). Thus, the chemical composition of other solar system bodies is usually given relative to that of the CI-type chondrites that are quite rare (i.e., 5 meteorites among the approximately 3000 distinct meteorites recovered to date). Amazingly, their initial mineral assemblage, which has so effectively locked such primitive unfractionated abundances (i.e., that expected from the pristine mineralogy of solar nebular condensates), has been completely devastated by aqueous alteration, and transformed into chunks of clay. In particular, chondrules and CAIs are not observed in CI chondrites.

There are two extreme views about this CI mineralogical chaos. Conventional view postulates that a unique "terminal" process of aqueous alteration occurred in the closed chemical system of the CI parent bodies, in order to preserve chemical primitiveness astonishingly well. The other challenging view is that in this world of chaos, it cannot be excluded that chondrules and CAIs were never present in the formation zone of the CI-type chondrites. In this case, the CIs should have been formed outside the volume of action of the kind of giant "conveyor-belt" system that transported chondrules and CAIs formed at high temperatures near the early Sun to the cooler formation zones of the other chondrites (see Sect. 24.1).

The isotopic chaos is even more impressive and mysterious. The bulk analysis of the oxygen isotopic composition of the various groups of chondrites already reveals that they were formed in different oxygen reservoirs (Clayton, 1993). The latest version (NanoSIMS) of the powerful ion analyzers developed by George Slodzian (see Sect. 28) greatly complicates this issue. It allows the measurement of the isotopic composition of oxygen on a scale of about 0.1 μm, in individual tiny components of these chondrites. In chondrites with a metamorphic grade ≤ 5, each component now shows its own oxygen isotopic composition, and this composition is different from both the bulk value and those of its closest neighbors! Such key features, which could not be detected with the mass spectrometers previously used for bulk analyses, illustrate the existence of a strong isotopic microscopic heterogeneity in the early solar nebula, which remains poorly understood.

As recollected by Burke (1986), Dodd (1981), who could not know about this "microscopic" isotopic chaos in these earlier times, already summarized the complexity of the meteorite classification while considering that "an estimate of 70 to 80 distinct parent *bodies may prove to be too low than too high"*. He was quite right. Nobody, yet, took the risky challenge to claim that this number is too high. In fact, Meibom and Clark (1999) estimated that there are about 135 distinct parent bodies. What a stunning difference with micrometeorites, dominantly related to CM chondrites!

Beware! Chaos is again camouflaged in this simple relationship, because there are major differences betweens AMMs and CMs (see Sect. 25.4). They include:

– the much higher pyroxene to olivine ratio of AMMs about 10–20 times higher than the value measured in CMs;
– the existence of ferrihydrite in AMMs, which is replaced by another type of Fe-rich poorly crystallized phase in CMs (tochilinite);
– the existence of saponite as the major hydrous silicate in AMMs.

7 The Major Contribution of Micrometeorites to the Delivery of Hydrous–Carbonaceous Material to the Earth

Micrometeorites and meteorites. The mass flux (number of tons, per year, for the whole Earth) of meteorites and micrometeorites can be estimated, both before and after atmospheric entry, from the works of Haliday et al. (1989), Zolensky et al. (1992), Love and Brownlee (1993), Bland et al. (1996), Hammer and Maurette (1996), Gounelle et al. (1999) and Duprat et al. (2003, 2004).

In the early 1990s, we mostly worried about the transmitted mass flux of meteorites and micrometeorites, which was not destroyed upon atmospheric entry. Indeed, it was thought that only this surviving material could have been effective in the prebiotic chemistry of life (Part IV). At this time, values ranging from about 2000 to 100,000 tons per year were reported for the micrometeorite flux –this value include the contributions of both unmelted micrometeorites and melted micrometeorites coined as cosmic spherules.

But recently, the counting of the total number of unmelted micrometeorites and cosmic spherules per ton of fresh snow collected near the Concordia station, at Dome C, in central Antarctica (see Sect. 22.4) gave the most reliable estimate of this transmitted mass flux. This was due to the conjunction of the following favourable circumstances:

– glaciologists monitored the precipitation rate of the snow at this site ($\sim$3.5 cm of water equivalent) over the last decade. This value then allows one to transform one ton of snow into an equivalent collector surface of about 28 m^2 exposed one year in the micrometeorite flux;
– the use of a gentle technique of collection;
– the incredibly small ($\leq$50%) contamination of the glacial sand in terrestrial dust grains allowed to identify and characterize individually for the first time all terrestrial and extraterrestrial particles recovered from the snow. This eliminated the major bias of selecting first the particles under a low magnification microscope when the proportion of terrestrial dust particles gets too large ($\geq$80%) –see a discussion of collection and sample processing biases in Sect. 27).

We found that the transmitted mass flux of unmelted micrometeorites and cosmic spherules reaching the Earth's surface after atmospheric entry was about 20,000 tons per year, while the pre-atmospheric flux is about 40,000

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tons per year (Love and Brownlee, 1993). As the abundances of both types of particles were rather similar, the mass flux of unmelted micrometeorites (including scoriaceous and fine-grained types showing similar abundances) is about 10,000 tons per year. This yields a mass flux of Fg-micrometeorites of about 5000 tons per year, as compared to about 10–20 tons of meteorites.

However, the domination of micrometeorites is even larger if one just focuses on hydrous–carbonaceous materials, which are capable of generating the early oceans and their associated *prebiotic soup*. Indeed, only about 3% of the meteorites are HCCs. Therefore, during a typical year, HCCs would deliver to the Earth's surface about 0.3 to 0.6 tons of hydrous-carbonaceous material to be compared to the mass of 5,000 tons delivered by micrometeorites. Consequently, if the contribution of hydrous-carbonaceous meteorites to this delivery rate was not increased by a factor ≥1000 on the young Earth, their contribution to prebiotic chemistry would have been probably quite negligible. What's about the contribution of asteroids and comets impacting the Earth to the delivery of this precious hydrous–carbonaceous material considered as the compost of life?

Comets and asteroids with sizes ≥1 km are not sufficiently decelerated in the atmosphere. They were destroyed upon impact during a kind of chemical explosion as induced for example by TNT. During such cataclysmic explosions their organics are destroyed and mostly transformed in to CO_2, H_2O and N_2. As their incident mass flux deduced from Fig. 20 is already rather similar to that of micrometeorites before atmospheric entry, they certainly played a minor role in the delivery of "intact" hydrous–carbonaceous materials that fed the prebiotic chemistry of life.

However, they could have delivered large amount of volatiles during these explosions in order to feed the formation of the early oceans and the amounts

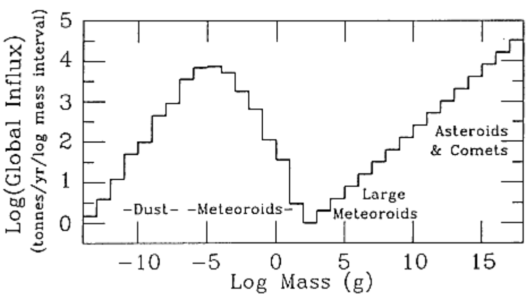

Fig. 20. Differential distribution of the mass influx rate to the Earth as a function of the mass of the impactor, obtained by binning the objects by logarithmic intervals of mass. The peak on the left, which reflects the contribution of micrometeorites, was derived from previous studies of visible and radar meteors. The distribution on the right, which is relevant to impactor masses bracketed between 10^{-7} and 10^{18} g, was estimated by Kyte and Wasson (1986) from studies of lunar impact craters (Courtesy of D. Steel).

neon and nitrogen in the air. The problem of assessing the contributions of both asteroids and comets to the budget of volatiles on the Earth is tricky. We just discuss below a few simple observations that help constraining these contributions.

Iridium and osmium in deep sea sediments. Kyte and Wasson (1986), conceived the bizarre mass distribution reported in Fig. 20 to interpret their depth profile measurements of the iridium content along a ∼9 m long piston core of deep sea sediments covering a time interval of about 30 Myr. They thus got a total mass influx of extraterrestrial material to the Earth (i.e., including micrometeorites, comets and asteroids) of about 78,000 tons yr^{-1}. This innovative plot helped to compare data covering 38 orders of mass magnitudes between 10^{-12} and 10^{18} g! The distribution on the left that was mostly deduced in the early 1980's from meteors studies in the radar and visible ranges (Hughes, 1978). It yielded a micrometeorite mass influx of about 16,000 tons yr^{-1}. It was compared to the total mass locked in the distribution on the right (about 68,000 tons yr^{-1}), which was estimated with the method of lunar impact craters –see Sect. 23.4, 2nd Subsect.

But in these earlier times the geochemical behaviour of the Ir terrestrial contamination that spoiled the "meteoritic" contribution could not be fully apprehended. Two years later Esser and Turekian (1988) carefully analysed this contamination. They pointed out that "*the mere presence of Ir and Os in a deep-sea sediment or in a continental ice-cap is not an unambiguous indicator of an extraterrestrial provenance*". They inferred a maximum value of the accretion rate of CI-type chondrite material of about 4.9–5.6 $\times 10^4$ tons per year that they deduced from the concentration and isotopic composition of osmium in a sampling of deep-sea sediments covering a time span of 0.3 Myr. And 7 years later, Love and Brownlee (1993) showed that the micrometeorite mass flux before atmospheric entry (about 40,000 tons per year) is about 2.5 times larger than the value inferred from meteor studies.

Consequently, these successive revisions of Fig. 20, showed that the micrometeorite contribution dominates clearly the "residual" contribution of crater forming impactors, of about 9,000–16,000 $\sim$ 12,000 tons per year, as assessed for bodies with a density of 3 g cm^{-3}. Therefore, comets would yield a corresponding mass influx about 3 times lower, which would turn to be about 10 times smaller than that of micrometeorites. This proportion is compatible with those deduced from deuterium in the oceans (see next Subsect.) and the dynamics of the outer solar system (see Sect. 23.3, last Subsect.). In brief, there is now a simple relationship that relates the total mass influx of comets, M_{TC}, over the time interval of about 0.3 Myr considered by Esser and Turekian, to the total mass influx of micrometeorite, $\Phi(t)$, over the same time interval:

$$M(t)_{TC} \sim 0.1 \times \Phi(t)$$

Then, we just extended this relationship to the time interval since the formation of the lunar crust at a time, $t_1 = 4.44$ Gyr. The value of $\Phi(t_1) \sim 5 \times 10^{24}$ g will be considered as a kind of unit of mass influx in this book. It was just derived from the neon and nitrogen contents of micrometeorites and the total amounts of these two volatiles measured in the Earth's atmosphere, without worrying about either the LHBomb or the nature of the parent bodies of AMMs (see Sect. 10.3).

Constraints from SMOW water and the planetary dynamics of the outer solar system. The total mass of the oceans is about 1.4×10^{24} g, and the average isotopic composition of their waters, as scaled by their average D/H ratio, defines the standard value SMOW (Standard Mean Ocean Water). From all known terrestrial samples, the constituent water of the hydrous silicates of AMMs give the best fit to the SMOW ratio of $\sim 1.5 \times 10^{-4}$ (see Sect. 9.2, 2nd Subsect., and, Sect. 29.5).

But the D/H ratio of the water of a comet's enveloping coma (i.e., the rarefied atmosphere produced during the sublimation of their ice), which has been measured for 3 comets from the Oort cloud, is about two times higher (see Fig. 22). This is an enormous difference in isotopic geochemistry. For this reason, it was already deduced that comets could not have delivered more than about 10% of the ocean water –see Morbidelli et al. (2000) for a review of previous works. As water is the dominant species of comets with a concentration of up to 80 wt.% (see Boyce and Huebner, 1999), the upper limit for their total mass infall, $M(t_1)_{TC}$, is about 1.7×10^{23} g, i.e., a value about 30 times smaller than $\Phi(t_1) \sim 5 \times 10^{24}$ g. We thus deduce that:

$$M(t_1)_{TC} \sim 0.034 \times \Phi(t_1)$$

Gomes et al. (2005) found another independent estimate of the total mass infall of comets in the arsenal of the dynamics of the outer solar system. They quote that the total mass of comets that struck the Moon since its formation includes a first component of about 5×10^{21} g, which was delivered before a late spike of comets, of about 9×10^{21} g, which struck the Moon between about 3.8–3.9 Gyr ago. The total mass of these two components ($\sim 1.4 \times 10^{22}$ g) can be extrapolated to the Earth taking into consideration the gravitationally enhanced cross section of the Earth for comets by a factor of ~ 13 (see Sect. 21.1, 4$^{\text{th}}$ Subsect.). This yields a total mass of comet striking the Earth, which well fits the upper limit just deduced from deuterium in the oceans:

$$M_{TC} \sim 1.8 \times 10^{23}\text{g} \sim 0.036 \times \Phi(t_1)\ ,$$

Constraint on asteroids with water and nitrogen. We cannot use the SMOW value to constraint the total amount of asteroids that struck the Earth, relatively to $\Phi(t_1)$, because the average D/H ratio of CM-type meteorites is close to the SMOW value (see Fig. 22). But we can try to use the total amount of either water and nitrogen stored on the Earth, $M(H_2O) \sim 1.4 \times 10^{24}$ g and $M(N_2) \sim 4 \times 10^{21}$ g, in conjunction with the corresponding wt.% concentrations, A(%) of these two elements in CM-type meteorites (of about 10% and 0.14%, respectively), to deduce the total mass, $M_T(CM)$ of CM type asteroids that should have struck the Earth since the formation of the lunar crust through the relationship $M(A) = A(\%) \times M_T(CM)$. Taking $\Phi(t_1)$ as a mass unit, one find:

$$M_T(CM) \sim 0.5 - 2.8 \times \Phi(t_1)$$

But was this huge mass available in the asteroidal belt? The total mass of asteroids in the current main belt represents about 4 wt.% of the mass of the Moon of about 7.3×10^{25} g. Then, Gomes et al. (2005) supported recently an earlier estimate of Arnold (1964). They found that this mass was initially at most ∼10 times larger than today (∼3×10^{25} g). The measurements of Ivezic et al. (2005) indicates that the proportion of "blue" asteroids made of a carbonaceous material is about 70%, either inside the belt, or in the population of NEOs, which are on Venus-, Earth- and Mars-crossing orbits, and which can strike the Earth. We don't know the proportion of CM-type asteroids in this dominant family of "blue" asteroids. We can only approximate its value by the proportion of CM-type chondrites among the carbonaceous chondrites, of about 35% (see Fig. 13). In this case the total mass of CM type asteroids in the early asteroidal belt was about:

$$M_T(CM) \sim 3 \times 10^{25} \times 0.7 \times 0.35 \sim 7.3 \times 10^{24} \sim \Phi(t_1)$$

The comparison of the two values of $M_T(CM)$ indicates that all the mass of the early asteroidal belt should have struck the Earth as to deliver the right amount of water and nitrogen! I can take my favorite powerful megaphone (it was used about 50 years ago to protest on a barricade) to shoot for the first time in this book "IMPOSSIBLE". When the Earth is viewed at 3 AU it looks like a tiny dot, with a minuscule surface to intercept asteroids. Moreover, the total mass of the NEOs that are in favorable Earth's crossing orbits is about 1000 times smaller than the main belt mass, and only a small proportion of them will end up striking the Earth. So, from now on, we could discard asteroids from our discussion. But who know? One of them could cataclysmically impact the Earth and destroy this proof reading if I am still checking it in a few years from now! So, we shall keep asteroids alive in this book.

A "Mumma" missing mass? In Fig. 20, there is a large gap that spreads from about 10^{-4} g to 10^{17} g. Our colleague M.J. Mumma (personal communication) wonders whether this anomalous gap might correspond to bodies now missing in the present day flux of extraterrestrial objects hitting the Earth, but which might have been quite abundant in earlier times as to feed the growth of the Earth's atmosphere. A "hand-made" reconstruction of the differential mass spectrum would shift the peak observed for micrometeorites to m-sized bodies. In this case, the flux of meteorites transmitted to the Earth's surface could have been much larger than that of micrometeorites.

But there is a severe constraint imposed on both the chemical and isotopic composition of these larger bodies (see Sect. 9.2). They should fit the "micrometeoritic" purity of the atmosphere. This is not the case either for the most favourable choice of wet asteroid (i.e., made of a material similar to the most water and neon rich HCCs) or for comets –see Sect. 8. Consequently, we believe that the gap observed in Fig. 1 already existed when the post-lunar Earth's atmosphere was made.

Delivery of micrometeoritic material during the late heavy bombardment. The basic assumption of the scenario developed to predict the effects of the accretion of juvenile micrometeorites on the early Earth during the LHBomb (see Sect. 10.4 in the next Part) was to assume that the impactors that heavily cratered the lunar highlands, and later on sparsely cratered the lunar mare, belonged to the family of bodies that were also the parent bodies of micrometeorites. In this case, the lunar cratering rate $K(t)$ reported in Fig. 1 would just scale to the amplification of the micrometeorite flux, relative to the present day value (before atmospheric entry), $\varphi_0 \sim 40{,}000$ tons/year. It can be directly extrapolated to the Earth because crater shape parameters (i.e., the diameter and the depth of a crater corresponding to a given kinetic energy of the impactor) are only slightly affected by gravity. Consequently, the total mass influx of micrometeorites on the Earth, $\Phi(t_1)$, since the formation of the lunar crust at time, t_1, is just given by the product of the integral of $K(t)$ and φ_0. There is also a simple scaling law that relates the total mass influx of comets, M_{TC}, and micrometeorites, $\Phi(t_1)$. We are now ready to move to the origin of the Earth's atmosphere, which has been hotly debated since the pioneering work of Rubey in 1951.

Part III

Formation of the Post-Lunar Earth's Atmosphere

8 The Inadequacy of Previous Scenarios

8.1 Competing Scenarios

According to the definition of Ozima and Podosek (2002), the Earth's atmosphere refers to all volatiles in surface reservoirs, including air, water and sedimentary rocks such as carbonates in which early CO_2 is now trapped.

Over the last 50 or 6o years, the formation of the atmosphere was successively attributed to a variety of scenarios, including:

- Volcanic outgassing, which recycled a mixture of volatiles trapped in the mixture of materials that fed the growth of the young Earth (Rubey, 1955). These volatiles might have been inherited during either the two distinct stages of accretion of the Earth, and/or the earliest solidification phase of the upper mantle, which got loaded with gases dissolved in equilibrium with the dense pre-lunar atmosphere;
- The direct capture of gases from the solar nebula (Urey, 1952);
- The explosive cataclysmic impact of comets (Owens, 1998; Delsemme, 1997);
- the impact of a giant "wet" asteroid with a size of ∼1500 km (Morbidelli et al., 2000);
- The post-lunar accretion of a giant long duration storm of "juvenile" micrometeorites, similar to the large hydrous-carbonaceous micrometeorites recovered from Antarctica (Maurette et al., 2000, 2001).

The major purpose of this chapter is to explain how we were progressively convinced about the validity of this last scenario, called early micrometeorite accretion (EMMA). One of the most simple tests to be applied to any scenario is to estimate the chemical composition of its predicted atmosphere, as defined by the Ne/N_2, H_2O/N_2 and CO_2/N_2 ratios deduced from the concentrations (in wt.%) or the total amounts of these four key volatiles in this atmosphere. Such predicted compositions are next compared to that of the present day atmosphere directly determined from the measurements of their total amounts.

In planetology, a difference by a factor 2–3 between predictions and observations is still considered as a "good" fit when going so far back in time. Problems arise when the differences clearly exceed that range of values. One

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has then to find credible processes to modify the model atmosphere, in order to generate the real atmosphere. For example, the very low concentrations of CO_2 in the terrestrial atmosphere (∼0.03%) could be considered somewhat anomalous, with regard to the much higher value found in the two terrestrial planets that frame the Earth, Venus (∼96%) and Mars (∼95%), until a reliable estimate of the total quantity of carbonates sediments on the Earth was available (Anders and Grevesse, 1989) –they result from the dissolution of early CO_2 in water, leading to bicarbonates and then subsequent deposition as carbonate sedimentary rocks. This estimate of about 270 millions km^3 corresponds to an initial partial pressure of CO_2 of about 60 bars, about 100,000 times higher than the small present day value.

8.2 Volcanic Outgassing, Accretion of Nebular Gases and Cometary Impacts

The two first processes are generally disregarded today –c.f., (Owens, 1998) and (Delsemme, 1997). In particular, Hawaiian volcanoes eject gases generated by the most primitive deep-seated magma originating from the primitive Earth's mantle. Their H_2O/N_2 and CO_2/N_2 ratios of about 10 and 4, respectively, do not fit at all the corresponding ratios measured for the atmosphere (Table 1, column 4). About the capture of nebular gases, the $^{20}Ne/N_2$ ratio of the solar nebula is given by the value (∼2) measured in the solar photosphere (considered to be a chunk of the solar nebula), which is about 10^5 times higher than the atmospheric value.

A few scientists still invoke the impact of cometary ices with the Earth. Such ices were impregnated with nebular gases during their formation –see Owens (1998) for a review of previous works. A preferential adsorption of the heavy noble gases from the nebula in the ices could possibly account for their odd mass fractionation in the atmosphere, illustrated in particular by the stumbling problem of the "missing" xenon, which is still considered by most scientists as one of the major constraints on the origin of the atmosphere –see Ozima and Podosek (2002) and Sect. 28.1.

However, the general consensus is that the direct hits of comets on the young Earth delivered less than ∼10% of the ocean's mass. –see Sect. 7, 3rd Subsect. This minor role of comets is also revealed by our simple test of chemical composition concerning the average H_2O/N_2 and $(CO_2 + CO)/N_2$ ratios of their transient atmosphere of about 30 and 2–6, respectively the data necessary to evaluate these ratios have been found in Delsemme (1997) and Boyce and Huebner (1999), produced during the sublimation of their "dirty" ices in the inner solar system. They do not fit the corresponding atmospheric values (column 4). However, one should be aware that the D/H ratio measured in the cometary tail is possibly different from that of the parent cometary ices and that the isotopic composition of water ices of EdK-belt comets and Oort cloud comets might be different.

8.3 A Wrong Neon for the Giant *"wet"* Asteroid?

After this screening, one of the two remaining models is the impact of a giant wet asteroid (GwetA) first proposed by Wänke (1981). In this still popular scenario, the volatiles released during the cataclysmic explosive impact of a giant wet asteroid (GwetA) with the Earth formed the atmosphere –see Javoy (1998) and Morbidelli et al. (2000) for the latest versions of this scenario.

Its composition is adjusted in order to yield the right amount of ocean water (1.4×10^{24}g) but also the "minimum" asteroid size, as to avoid a marked heating during its formation, due to radioactive decay and accretional heat. This last condition is important as a modest formation temperature in excess of about 600 K effective over about 1 Myr would already trigger an important loss of the constituent volatiles of the GwetA before its impact with the Earth. The most favorable assumption is to assume that its bulk composition is just similar to that of an undegassed "chunk" of the most water-rich meteorites ($\sim$20 wt % of water), the CI-type chondrites (CIs) –see Sect. 6. A "minimum" size of about 1500 km is deduced from this remarkably high water content, corresponding to a body made of about 100% clay! This body is already sufficiently massive to probably suffer a noticeable degassing during its formation.

However, the assessment of its exact state of dehydration cannot be made through visible and near-infrared reflectance spectroscopy (Gaffey et al., 1989), because such hydrous "giants" do not exist any more. The situation with the two largest asteroids still existing to day is fairly confusing. The largest asteroid (Ceres) with a size of 940 km appears to be a hydrous–carbonaceous asteroid, while the second largest asteroid (Vesta), with a size of only about 525 km, is already made of differentiated rocks resulting from the cooling of magma.

The misleading "bulk" solar neon of HCCs. The bulk average contents of neon and nitrogen in CIs, of about 3.10^{-7} cc STP/g and 0.26%, respectively (Mason, 1971), already show that a CI type *GwetA* would deliver an atmosphere with a Ne/N_2 ratio about 100 times smaller than the value measured in the Earth's atmosphere. In the odd unit of cc STP/g used by geochemists (STP is the acronym for "Standard conditions of Temperature and Pressure"), 1cc STP of neon per g of material is equivalent to about 0.1 wt%. Nevertheless, the real misfit between prediction and the corresponding observations is even worse. It started to be decrypted recently (Maurette, 2002), relying on studies of the reprocessing of material in extraterrestrial regoliths (c.f., Sect. 3.2).

The key observations leading to this tricky misfit is that HCCs are all regolith breccias, like most rocks found on the lunar surface. They are compacted chunks of the loose layer of debris, coined as regolith, which tops the surface of both the Moon and large asteroids. Before their compaction into breccias, these debris suffered gardening by repeated impacts, which induced their complex depth history in the regolith. Langevin retraced the depth history of many test particles in such regoliths with a Monte Carlo computer code nicknamed "SOLMIX" (see Sect. 3.4). It was found that only about 10% of the particles resided on the top surface of the regolith of large asteroids, where they were implanted with solar neon.

The predictions for asteroids are well compatible with recent observations of Nakamura et al. (1999), based on laser microprobe studies of the distribution of neon isotopes in about 100 µm size zones of thin sections of two of the most gas-rich HCCs–Nogoya and Murchison, which belong to the most abundant CM-type subgroup of HCCs. Their petrographic and mineralogical characteristics were first carefully investigated. As expected from SOLMIX about 10% of the grains are "gas-rich" grains, loaded with solar neon up to the high average contents of about (1–3) $\times 10^{-5}$ cc STP/g, observed in both micrometeorites and "mature" lunar soil samples. But as CM-type HCCs contain only 10% of these gas-rich grains, their bulk content of solar neon is about 10 times smaller than the micrometeorite value. What about neon in the dominant fraction of the gas-poor grains?

New hints from the gas-poor grains of HCCs. The family of gas-poor grains represents about 90% of the HCC mass. In the case of the CMs, most of them belong to centimeter-sized "clasts" of a material defined as "Primary Accretion Rock" (PARs) in which they were shielded from the implantation of SW and SEPs neon. Consequently, they do not contain solar neon, even though their parent clasts might have been exposed to solar neon on the top surface of the regolith. Instead, they show a very different residual neon component called primordial, and characterized by both a smaller concentration and a much smaller ^{20}Ne/^{22}Ne ratio (≤ 8). *This component, which has not been contaminated by solar neon, should be similar to that trapped in rocks below the regolith, well shielded from SW and SEPs neon, and which represents ~99.9% of the mass of a 1500 km-sized GwetA.*

The average content of primordial neon in the PARs is about 5.10^{-8} cc STP/g –see "pits" 59 and 60 in Fig. 6 reported by Nakamura et al. (1999). This content can be reasonably extrapolated to the CIs –and thus to the GwetA– because it was measured in the *PARs*, which were also shown to be the building blocks of the parent bodies of the CIs (Eiler and Kitchen, 2003). Furthermore, the content of nitrogen (~2500 ppm) is rather similar within a factor 2–3 in the CIs and CMs (Mason, 1971), and consequently in the GwetA. Indeed, this element does not result from a regolith contamination because it is carried by the carbonaceous component of meteorites. Consequently, if the early atmosphere was delivered by an HCC type GwetA, its Ne/N_2 ratio should be about 1000 times smaller than the atmospheric value!

The wrong neon isotopic composition of a CI-type GwetA. There is another inadequate prediction, which deals with the nature of neon in the early atmosphere. There is a general consensus that this neon was "solar", being characterised by a high ^{20}Ne/^{22}Ne ratio bracketed between 13.8 and

11.2 (see Sect. 19). Subsequently, a mass dependent process of isotopic fractionation did trigger a preferential loss of the lightest ^{20}Ne isotope, which decreased this initial solar ratio to the atmospheric ratio of 9.8. But the GwetA model would generate an early atmosphere showing a very different heavy "primordial" neon, with a ^{20}Ne/^{22}Ne ratio (≤ 8) now smaller than the atmospheric value. To be compatible with the atmospheric ratio of about 9.8, this low initial value would require a preferential loss of the heaviest ^{22}Ne isotope through a mysterious unnatural process, still to be discovered!

This "double-misfit" between predictions and observation was hard to detect because it was "camouflaged" in the complexity of the regolith-reprocessing of planetary material. In brief, the bulk solar neon of HCCs reflects a negligible and misleading surface contamination of the GwetA, and not its bulk "primordial" composition. In contrast, studies reported in the next section indicate that the constituent neon of micrometeorites now simultaneously yields this solar composition and the right Ne/N_2 atmospheric ratio. This "double-fit" initiated the vision that the formation of the early Earth's atmosphere might be due to a giant long duration "storm" of juvenile micrometeorites. We now use additional experimental observations that further support this suspicion, without relying on questionable models, which generally contain hidden adjustable parameters used to fit expectations to observations.

9 A Prime Suspect for the Formation of the Atmosphere

The chemical composition of the Earth's atmosphere can be defined by the $Ne/N_2, H_2O/N_2$ and CO_2/N_2 ratios deduced from the total amounts of these four volatiles in the atmosphere. The same volatiles are released by hydrous–carbonaceous micrometeorites upon frictional heating as to generate a micrometeoritic model atmosphere. Its composition is inferred from the weight % contents of Ne, N_2, H_2O and carbon that were measured in about 500 Antarctic micrometeorites from the 100–200 μm size fraction. The composition of the micrometeoritic atmosphere was thus found to be strikingly similar to that of our blue planet.

9.1 Concentrations of Volatiles in Antarctic Micrometeorites

Neon. Noble gas analyses indicate that the neon trapped in unmelted AMMs has a solar isotopic composition (^{20}Ne/^{22}Ne $\sim$ 11.8) and an average concentration of $\sim$ (1–3) $\times 10^{-5}$ cc STP/g (Olinger et al., 1990; Maurette et al., 1991; Nakamura and Takaoka, 2000; Osawa et al. 2000, 2002). This put micrometeorites on par with lunar dust grains. They both represent the most gas-rich extraterrestrial material known as yet, with the exception of the minor fraction ($\sim$10%) of the constituent gas-rich grains of the "gas-rich" meteorites, which show similar high solar neon contents.

In Sects. 10.6 and 19.3 we justify our belief that both the content and isotopic composition of neon in unmelted micrometeorites has not been markedly affected by frictional heating upon atmospheric. This is related to a severe reprocessing of these two characteristics during the exposure of micrometeorites to very high fluences of solar wind helium during their long flight times to the Earth in the interplanetary medium.

Nitrogen. The measurement of the upper limit ($\sim$0.1%) of the nitrogen concentration reported in Table 1 (column 2) was made in June 1988 (i.e., 3 months about our first collect of Antarctic micrometeorites). But it took us $\sim$12 years before getting the lower value (0.03%) of this concentration, from which a reliable estimate of an average concentration of nitrogen in AMMs (about 0.07%) was deduced.

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A few months after our first AMMs collect of January 1988, we did use an electron energy loss spectrometer (EELS) associated to a high voltage transmission electron microscope to search for the peaks of C and N expected around 300 and 400 eV, respectively. Carbon was easily detected in all AMMs. However, only a few of them gave a weak nitrogen peak above background, which was too small to be quantified. This gave an upper limit of the nitrogen content corresponding to the limit of sensitivity of this technique of microanalysis of about 0.1%. But it took us ~12 years before reconfirming this upper limit and getting the lower limit of this concentration of about 0.03%.

Matrajt et al. (2001, 2002, 2003) measured the C and N contents of both AMMs from the Cap-Prudhomme and the South Pole collections, small stratospheric micrometeorites and ~100 μm size fragments of both Murchison and the odd Tagish Lake meteorite related to the CM- and CI-type chondrites, respectively. They relied on a nuclear microprobe with a much-improved lower limit of detection allowing analysis on a spot of about $5 \times 5\,\mu^2$ (see caption of Fig. 16), which was developed by J.P. Gallien and his team. This instrument yields micromappings of the C and N concentrations from which the C and N concentrations and the C/N ratios can be inferred. The validity of the technique was established noting that the nuclear microprobe results well fit the values inferred for the two meteorites with the powerful technique of stepped combustion (see Sect. 29.7).

These analyses were already illustrated in Fig. 16 for a fine-grained AMM. Figure 21 show the micromapping obtained for the more strongly heated up scoriaceous type AMMs (see Sect. 6.3 and Fig. 14 for the classification of AMMs on a metamorphic scale). These micromappings yield the average nitrogen contents of AMMs and their C/N ratios, which corresponds to the range of values typical of natural kerogens (about 20–50). The *maximum* average value of 0.09%, which was obtained for a fine-grained AMMs (K4C) from the South Pole collection, well agrees with our earlier upper limit of 0.1%. The scoriaceous particles are loaded with vesicles related to the partial lost of their volatile species during their strong but very short frictional heating upon atmospheric entry. Their *average* nitrogen content of about 0.03% was inferred from the 3 scoriaceous AMMs investigated by Matrajt et al. (2003). It gives a true lower limit of the initial value of the nitrogen content of micrometeorites before atmospheric entry, because nitrogen was partially lost upon atmospheric entry. Note that all this lost nitrogen was trapped in the atmosphere anyway.

Water. Hydrous silicates are the host phases of H_2O and OH radicals in micrometeorites, and their abundances yield the lower limit of the water concentration of micrometeorites. In our two first contributions (Maurette et al. 2000, 2000b) we did use a content of hydrous silicates of about 20%, which yielded a bulk water content of ~4%. But Gounelle (2000) found that this value was severely underestimated when the major hydrous silicates of AMMs

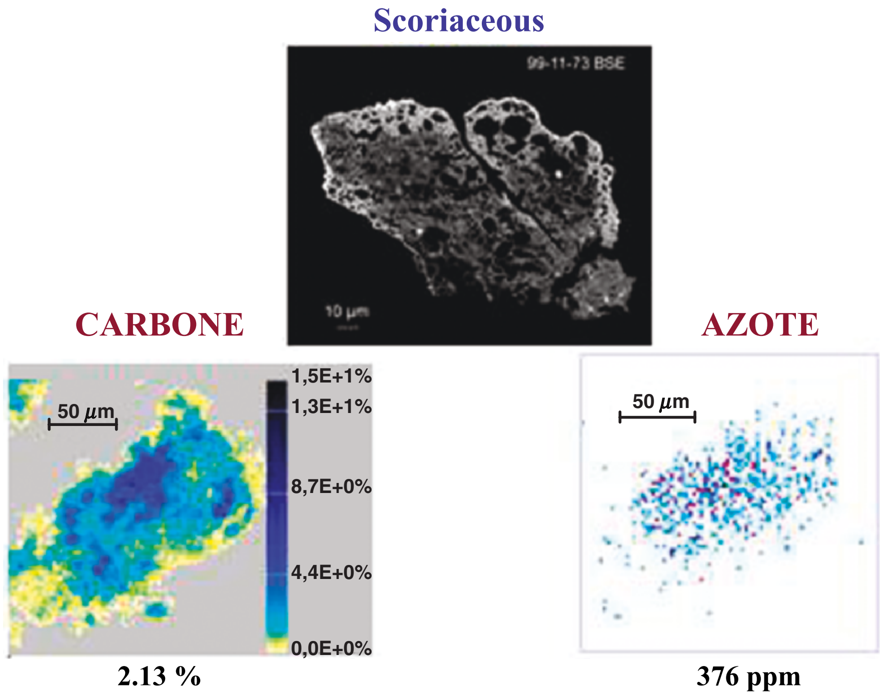

Fig. 21. Micromappings of the carbon and nitrogen distributions in a scoriaceous-type Antarctic micrometeorite, which were obtained with a nuclear microprobe (see caption of Fig. 16). This type of particle, which was more strongly heated upon atmospheric entry than the fine-grained variety reported in Fig. 16, yielded the lower value of the nitrogen content of micrometeorites used in this book, of about 300 ppm (Courtesy G. Matrajt).

(saponite and serpentine with serpentine being about twice as abundant as serpentine) could be identified through their highly typical relict chemical composition, even though they partially lost their constituent water upon atmospheric entry (see Sect. 25.2). The total content of hydrous silicates (∼50%) is now quite compatible with that inferred for the CM-type chondrites (where serpentine now is more abundant than saponite) and yields a water concentration of about 10% –see also Sect. 25.2. To get an upper limit of the concentration of water that could be released upon atmospheric entry, one adds the minor concentration of water that would be produced during the full oxidation of the constituent carbonaceous material of AMMs.

CO_2. The potential content of CO_2 that can be released by micrometeorites upon atmospheric entry can be estimated from the bulk carbon concentration of AMMs, which is mostly stored in both their carbonates and carbonaceous components. About ∼0.5% of the total carbon of AMMs is trapped as carbonates (Maurette et al., 1992) and their average organic carbon content is about 2.5% –this value was measured with the ion microprobe of *Centre de Recherches Pétrographiques et Géochimiques* (c.f., Engrand and Maurette, 1998). The lower limit reported in Table 1 corresponds to the decrepitation of carbonates and the upper limit is obtained adding the amount of CO_2 resulting from the full oxidation of the organic carbon. These carbon concentrations allow computing the potential content of CO_2 of micrometeorites, which can be released upon atmospheric entry and subsequently transformed into carbonates that will settle down to the ocean floors.

9.2 The Micrometeorite "Purity" of the Early Earth's Atmosphere

Chemical composition. The lower and upper concentrations of micrometeoritic volatiles, *A(%)*, have been reported in Table 1 (column 2), in wt %. Their ratios directly give the Ne/N_2, CO_2/N_2 and H_2O/N_2 ratios (columns 3) expected for the small puff of gases of a few mg that would be released upon atmospheric entry by the approximately 500 contemporary AMMs used to make the measurements of the *A(%)* values –these ratios are deduced from the arithmetic average of the lower and upper values of *A(%)* for each species. The turns to be strikingly similar (i.e., within a factor ∼2) to those deduced for he massive (∼2×10^{24} g) Earth's atmosphere (column 4), which is directly given by the ratio of the total amounts of the corresponding volatiles measured in the atmosphere (column 5). The next investigation was to check whether this striking similarity also extends to the isotopic composition of neon and water.

Table 1. Chemical composition of the "micrometeoritic" and present day atmospheres

Volatile species A	AMMs *A(%)*	Predicted (AMMs) A(%)/N_2*(%)*	Observed A(g)/N_2(g)	Atmosphere A(g)
Ne	(1–3) $\times 10^{-6}$	3×10^{-5}	1.6×10^{-5}	6.5×10^{16} (a)
N_2	(0.3–1) $\times 10^{-1}$	1	1	4×10^{21} (b)
H_2O	10–12	170	350	1.4×10^{24} (c)
CO_2	1.8–11	100	85	0.33×10^{24} (d)

[a] Measured in the air (Ozima and Podosek, 2002)
[b] Measured in the air (Anders and Grevesse, 1989)
[c] Mass of the terrestrial oceans (Chyba and Sagan, 1997)
[d] Deduced from the total mass of carbonates (Anders and Grevesse, 1989)

Isotopic composition of neon. Neon is considered to be one of the best tracers to decrypt the history of the Earth's atmosphere. It is not sequestered during chemical reactions and, with the exception of a minor fraction of ^{21}Ne, it is not produced during the decay of radioactive elements, contrary to helium and some isotopes of the heavier noble gases. Its isotopic composition in unmelted AMMs turns out to be "solar". It is bracketed between the ^{20}Ne/^{22}Ne ratios observed in the solar wind (SW) and solar energetic particles (SEPs) of about 13.8 and 11.2, respectively (Wieler, 1998). The average micrometeoric ratio of ∼11.85 was deduced from the accurate measurements reported by Nakamura and Takaoka, (2000) for aliquots of approximately 200 AMMs. It constitutes a unique signature of micrometeoritic neon that would reflect a specific distribution of their flight times to the Earth that allows the accumulation of the right amount of SW and SEP neon (Maurette and Sarda, 2004; see also Sects. 10.6 and 19.3).

It is generally assumed that neon in the early atmosphere initially has a solar composition (Ozima and Podosek, 2002). Subsequently, the high solar ^{20}Ne/^{22}Ne ratio was lowered by a preferential loss of ^{20}Ne triggered by mass dependent fractionation processes such as hydrodynamical escape (Ozima and Zahnle, 1993). Most models assume that this neon was not delivered by micrometeorites. It was initially incorporated during the formation of the building material of the Earth in the solar nebula, before the formation of the planets, and then subsequently degassed into the atmosphere. We offer another alternative, where this pre-lunar neon was blown off during the Moon-forming impact, thus leaving a new niche for the accumulation of a pure component of solar micrometeoritic neon in the atmosphere. This rejuvenates an earlier suggestion of geochemists, which was disregarded in the early 1990s (see Sect. 19).

Isotopic composition of water. The isotopic composition of the constituent water of individual HCCs and AMMs can be plotted as the distribution of their D/H ratios. In Fig. 22, we first reported the distributions measured for CI- and CM-type chondrites (upper histograms), which were deduced from data recently reported by Eiler and Kitchen (2003). The lower histogram refers to the distribution obtained from the ion microprobe analysis of 52 AMMs (Engrand and Maurette, 1998; Engrand et al., 1999). Other ratios include values measured for an average of the terrestrial oceans ("SMOW" value), Antarctic melt ice water, and 3 comets originating from the Oort cloud.

These distributions can be compared to those reported for much smaller micrometeorites collected in the stratosphere by NASA, which show much higher D/H ratios (see Fig. 49 in Sect. 26.1). It clearly shows that from all extraterrestrial material investigated yet, including cometary water, AMMs give the best fit to the SMOW value. It could be argued that they were contaminated by terrestrial water. But micrometeorites were recovered from Antarctic melt ice water, which shows the lowest D/H ratio measured on the Earth, about 1.5 times smaller than SMOW. Furthermore, experiments discussed in Engrand et al. (1999) indicate that isotopic exchange between

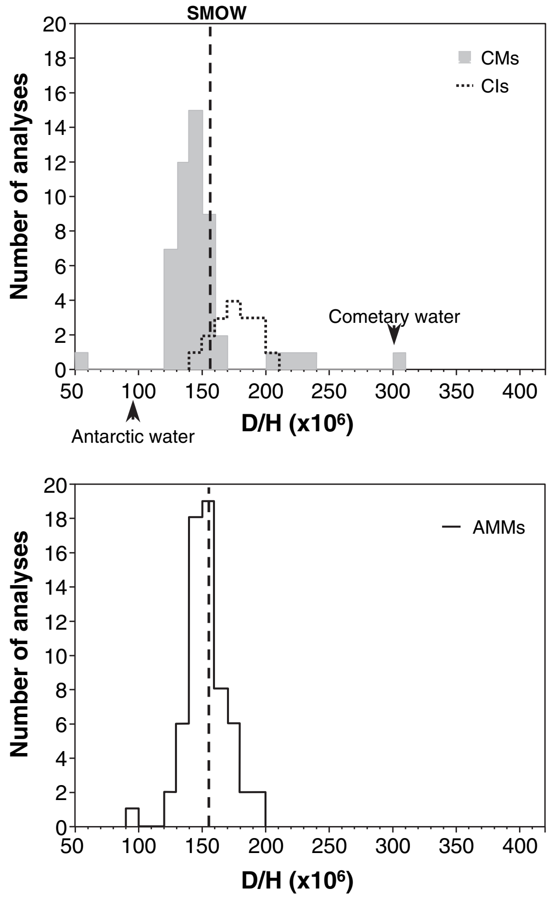

Fig. 22. Isotopic composition of various types of waters, including the constituent water of the CI- and CM-type hydrous-carbonaceous chondrites (upper histograms), and the constituent water of Cap-Prudhomme Antarctic micrometeorites (lower histogram). From left to right the arrows refer to: Antarctic melt ice water showing the lowest terrestrial D/H ratio; an average of the terrestrial oceans that defines the "SMOW" value; an average of the D/H ratios measured in three non periodic comets (Courtesy C. Engrand).

AMMs and terrestrial water is unlikely to have happened. Finally, the Cap-Prudhomme chondritic barred cosmic spherules are clearly not weathered to any significant extent (the etch canals resulting from the preferential etching of their glass bars have lengths $\leq 1\,\mu m$ in the worst case of the bottom spherule reported in of Fig. 31). They still show inside measurable concentrations of water ranging from 0.1–1.6 wt.%, which has the SMOW isotopic composition.

The astonishing similarity between the chemical and isotopic compositions of the terrestrial atmosphere formed about 4.4 Gyr ago (Sarda et al., 1985) and the mixture of gases released during atmospheric entry from a few milligrams of AMMs, which were accreted by Antarctica snow less than 50,000 years ago, is still hard to believe. It suggests that the suspect responsible for the formation of the atmosphere was the accretion of a huge flux of juvenile micrometeorites, with a composition very similar to that of AMMs. This deduction of an invariant composition now allows predicting the total amounts of micrometeoritic volatiles injected in the early atmosphere with a simple "accretion" formula.

10 Formation of the Post-lunar Atmosphere

The early Earth's atmosphere was much more massive than today. Before the condensation of water and the subsequent dissolution of CO_2 that precipitated into carbonates, the partial pressures of H_2O and CO_2 were about 270 bars and 60 bars, respectively. Today, planetary exploration has revealed that the atmospheres of 8 planets and 3 of their approximately 120 satellites have a structure rather similar to that deduced from the vertical temperature profile of the contemporary Earth's atmosphere, which shows that the temperature alternately decreases and increases with height (troposphere, stratosphere, mesosphere, and thermosphere). In particular, because the giant planets and Venus are all topped by a high-temperature low-density thermosphere (Dowling, 1999), we can safely assume that the early Earth had also a thermosphere.

This is the layer where most micrometeorites decelerate –i.e., between 120 and 80 km today. Moreover, in the upper thermosphere, the high velocity wing of the Maxwellian distribution of velocity allows some light atmospheric species to reach escape velocity at an altitude of ≥300 km today. During their frictional heating with air molecules, micrometeorites release volatile species and "smoke" particles, thus generating a kind of cosmic "volcanism" falling from the sky, which delivers the four test volatile species considered in our work. We now predict their total amounts in the atmosphere. Such predictions are based on:

- *the deduction that the composition of micrometeorites was invariant with time;*
- *the physics of the giant Moon-forming impact that did blow off the pre-lunar atmosphere (see Sect. 29.2);*
- *the relative lunar cratering rates conjectured by Hartmann, which reflect the variation with time of the flux of impactors with sizes ≥500 m, which bombarded the Earth/Moon system after the formation of the lunar crust,* 4.44 *Gyr ago.*

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10.1 The Invariant Composition of Micrometeorites with Time

In our scenario, the composition of the Earth's atmosphere reported in column 3 was produced by a total mass of micrometeorites accreted after the formation of the Moon (i.e., 4.45 Gyr ago) of about 5.10^{24} g (see Sect. 10.4). Amazingly, this composition turns to be quite similar to that expected from the degassing of a 5 mg sample of contemporary Antarctic micrometeorites with sizes of about 100–200 µm accreted by the Earth less than 50,000 yr ago. Consequently, these two families of micrometeorites, separated by a time interval of about 4.4 Gyr, would have the same composition of volatile elements, and thus the same parent bodies. Very different types of studies concerning the "meteoritic" contamination of either the lunar regolith or the regolith of the parent asteroids of HED meteorites support this deduction.

Ganapathy et al. (1970) and Wasson et al. (1975) first attempted to identify the nature of the interplanetary bodies, which contaminated the lunar soil. They used refractory platinum group metals (gold, osmium, iridium) as well as a rather volatile element (germanium), which are both extremely depleted in lunar igneous rocks, but much enriched in HCCs and AMMs. Wasson et al. (1975) thus reported correlation plots between the Ge/Ir and Au/Ir ratios measured in lunar soils samples formed about 3.7 Gyr ago. This plot has been recently completed by the analysis of new types of meteorites, which were not available in 1975 (Gounelle, 2000). It shows that from all types of extra-lunar material known at this date, and within the error bars, only a hydrous–carbonaceous material related to the CM- and CR-type HCCs (but not to the CI-type!) gives the best fit.

Zolensky et al. (1996) even found a large centimeter-sized foreign clast of CM-type material in a lunar soil, which survived miraculously well upon its crash on the Moon. Micrometeorites are both essentially related to CM-type chondrites and they deliver a much larger amount of hydrous–carbonaceous material than meteorites (see Sect. 7). Therefore, the measurements of Wasson et al. are well compatible with the deduction that the CM-type composition of lunar soil is due to juvenile micrometeorites accreted about 3.7 Gyr ago, which had a composition very similar to that of AMMs.

One can go further back in time to about 4.2 Gyr ago with stony meteorites of the "HED" achordrite group, and more specifically with Kapoeta. This is a breccia formed in the regolith of a differentiated (i.e., melted) parent asteroid. This peculiar meteorite has one of the oldest impact ages of about 4.2 Gyr, which dates its formation during an impact on its parent regolith (essentially made of fine-grained fragments of basalts). Zolensky et al. (1996) first showed that Kapoeta (and consequently its parent asteroidal regolith) accreted mm-sized inclusions (called clasts of foreign material) of CM-type material, which survived upon their impact in the regolith –they can be considered to be juvenile minimeteorites. Then, Gounelle et al. (1999,

2001) showed that Kapoeta also contains numerous 100 μm-size microclasts of CM-type material, which are real juvenile micrometeorites.

On polished sections they look like fine-grained AMMs imbedded into the dry basaltic matrix of the meteorite (Fig. 23). These microclasts are dominantly made of a primitive unequilibrated CM-type hydrous–carbonaceous material. Recent measurements of the D/H ratios of their constituent water by Engrand (Fig. 24) yielded an average ratio similar to the SMOW value measured in Antarctic micrometeorites with regard to the spread of the D/H ratios (Gounelle et al., 2003).

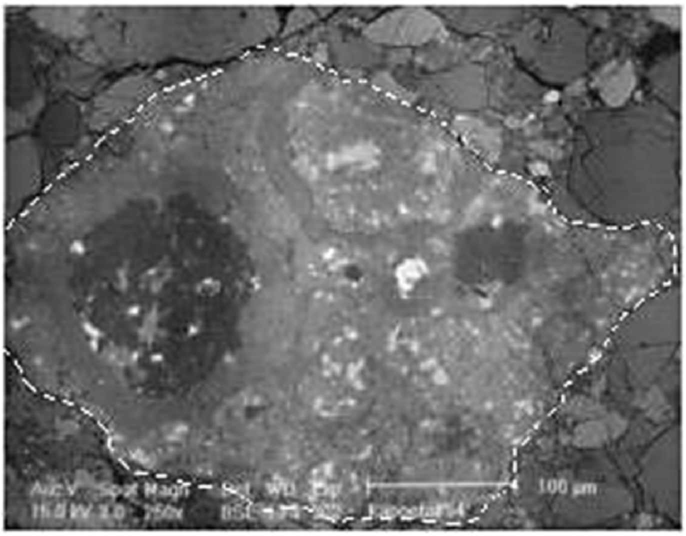

Fig. 23. SEM micrograph of a polished section of the Kapoeta howardite (a differentiated achondrite), which is a typical regolith breccia (scale bar 100 μm). It contains foreign microclasts of CM-type material, which are "fossil" micrometeorites accreted by the parent regolith of Kapoeta before its compaction into a rock, dated at about 4.2 Gyr ago. The microclast in this figure appears as the central brighter diamond-shaped phase that represents about 50% of the surface of the micrograph. The darker dominant matrix of highly fractured crystals of the host igneous meteorite surrounds it. This fossil CM-type micrometeorite is made of fine-grained hydrous silicates (saponite and serpentine), which contain complex aggregates of other minerals such as the darker circular aggregate observed on the left hand side, surrounded by a darker rind of hydrous silicates, which is probably some odd micro-chondrule. The non-destructive accretion of these fossil micrometeorites by the differentiated parent regolith of Kapoeta is still not understood (Courtesy of M. Gounelle).

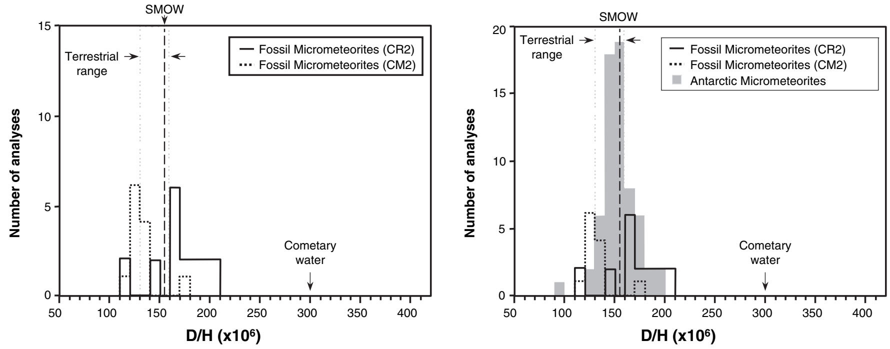

Fig. 24. Distribution of the D/H ratios of "fossil" micrometeorites found in the Kapoeta howardite. A comparison with the distribution noted for modern Antarctic micrometeorites unexpectedly shows that the spread of their distributions is very similar. Both distributions thus yield an average D/H ratio quite comparable to the SMOW value noted for the terrestrial oceans. (Courtesy of C. Engrand).

As a first approximation, we consider that the composition of the micrometeorite flux has been invariant with time and can be approximated by that measured in Antarctic micrometeorites. This invariance allows deriving the accretion formula, which is the backbone of EMMA. In Sect. 22.3 we argue that this invariant composition is most compatible with a cometary origin of most AMMs, even though astronomers investigating the chemical composition of molecular species released by the sublimation of cometary ices report noticeable differences between comets with regard to their "hypervolatile" species, such as CO and CH_4 (Mumma, 2002; Mumma et al., 2005).

10.2 An Accretion Formula Born with the Moon

The Moon was formed by the impact of a giant Mars-sized planetary embryo with the Earth, which occurred at time, t_1, and closed the formation time interval of the Earth, Δ $(Earth)$ –see Sect. 3.1. Accordingly to Ahrens (1993), this impact blew off the pre-lunar atmosphere. It thus left a vacant "niche" for the accumulation of a new "post-lunar" atmosphere. Our Japanese colleagues presented a new model of impact where only 20% of the initial Earth's atmosphere was blown off. But their model predicts a very complex composition of the Earth's atmosphere, which is invalidated by the measurement of its micrometeoritic purity, which is illustrated in Table 1 (see Sect. 29.2).

The invariance of the composition of the micrometeorites with time allows us to assume that the wt% content, $A(\%)$, of a given volatile, A, in early micrometeorites, back to t_1, is given by the corresponding value measured in Antarctic micrometeorites. If a method is found to estimate the integrated mass flux of micrometeorites, $\Phi(t_1)$, deposited on the Earth since t_1, the total amount, M_A, of A deposited by micrometeorites in the post-lunar atmosphere is given by a simple accretion formula: $M_A \sim [A(\%)/100] \times \Phi(t_1)$.

Time, t_1, is a critical parameter in our model, which was assimilated to the formation age of the lunar crust, of 4.44 Gyr (Carlson and Lugmair, 1988). This value yields a formation time interval of the Earth, $\Delta(Earth) \sim$ (4.56 Gyr–4.44 Gyr) $\sim$ 100 Myr, where 4.56 Gyr is the "age" of the solar system –see Sect. 3.1 for independent justifications of this value. The next sections briefly outline fully independent methods that unexpectedly yielded a similar value of $\Phi(t_1)$.

10.3 Two Estimates of $\Phi(t_1)$ from Neon and Nitrogen in the Atmosphere

During their aerodynamical braking in the thermosphere, micrometeorites, which were either fully volatilized and/or transformed into dry melted cosmic spherules, directly inject volatiles into the atmosphere. The study of the new Concordia collection of micrometeorites greatly helped to characterize for the first time the value of the micrometeorite flux reaching the Earth's surface, which was found to be made of about 50% cosmic spherules and 50% unmelted micrometeorites (the proportion of unmelted fine-grained micrometeorites was increased by a factor of 2 relative to previous estimates due to the discovery of a new population of highly friable micrometeorites, which were destroyed in all previous Antarctic collections. Furthermore it was found that their total mass flux of about 20,000 tons per year is only two times smaller than the value of 40,000 tons measured before atmospheric entry (Love and Brownlee, 1993).

Therefore about 75% of the incoming flux of micrometeorites with sizes $\geq$100 µm is destroyed by volatilization and melting, thus injecting volatiles directly into the atmosphere. Unmelted micrometeorites that survive upon atmospheric entry essentially settle down on the oceanic crust, and they are degassed at shallow depths during the subduction of their host crust. As a first approximation, the full incoming flux of hydrous–carbonaceous micrometeorites delivers volatiles to the atmosphere in agreement with our estimate that only 0.3% of the initial amount of micrometeoritic neon was transferred to the upper mantle (c.f., Sect. 19.4).

The invariance of the composition of the micrometeorite flux with time allows us to get two direct estimates of $\Phi(t_1)$ from the total amounts of neon and nitrogen in the atmosphere and the concentration of these two elementsin AMMs, which differ by a factor of $\sim$100,000 (see Table 1). For each element, these contents are bracketed between a lower and upper limit, which yield their average contents. One thus infers two values of $\Phi(t_1)$ of about 4.3×10^{24} g and 6.1×10^{24} g, from neon and nitrogen, respectively.

Each one of these values can already be considered as fully independent because neon and nitrogen in micrometeorites do not have the same origin (see Sect. 10.5). Each flux value allows the estimation of the total amounts of the three other volatiles, which already fit the observed amounts within a factor 2–3. This straightforward method has the unique advantage of being fully independent on any speculation about the early history of the micrometeorite flux and of the early Earth. However, it is not satisfactory because neon and nitrogen are key elements to reconstitute the history of planetary atmospheres. We thus derived a third fully independent method to estimate $\Phi(t_1)$, and thus the total amount of neon and nitrogen in the atmosphere. This method is now fully anchored in the period of the heavy bombardment of the Earth–Moon system.

10.4 A Third Independent Estimate of $\Phi(t_1)$ from the Lunar Impact Record

Estimate for micrometeorites. This estimate was derived from the smooth approximate exponential decay of lunar cratering rates, $K(t)$, relatively to the present day value (see Fig. 1 in Sect. 3.2), which decorates the post-lunar period of the late heavy bombardment. This curve gives a monitoring of the dominant family of crater forming bodies with sizes $\geq$500 m existing in the interplanetary medium at the Earth's orbit, at any given time since the formation of the Moon.

The basic assumption of EMMA is to consider that these bodies were extracted from the population of solar system bodies, which were also the dominant parent bodies of early micrometeorites. Therefore, if the flux of lunar impactors was multiplied by $K(t)$, the micrometeorite flux, $\varphi_0 \times K(t)$, was increased by the same factor, relative to the present day flux before atmospheric entry, φ_0. Therefore, $K(t)$ would directly scale to the variation with time of the amplification factor of the micrometeorite flux (relative to the present day value) after the formation of the Moon.

This assumption can be challenged on various grounds. Collisions and gravitational forces only rule the dynamic evolution of large objects. On the other hand, the orbits of interplanetary dust particles are further perturbed by non-gravitational forces that induce their steady spiralling to the Sun unless they collide with some particles.

We believe that the dominant parent bodies of micrometeorites are comets (see Sects. 7 and 22). In this case, lunar cratering rates would measure the flux of comets with perihelion smaller than 2.5 AU. Consequently, there would be a scaling between the impact record and the amplification of the micrometeorite flux even though the delivery of micrometeorites would have been slightly delayed by a few thousand years or so. Chyba and Sagan (1997) also scaled the net impact flux on the Moon to the Earth, relying on a lunar impact record very similar to ours, to compute the total mass of large impactors that struck the Earth in the time interval of about 3.5–4.4 Gyr ago (see Sect. 10.6).

The approximate exponential variation of $K(t)$ allows the integration of $\phi_0 \times K(t)$. Gounelle (2000) noted that the integrant is always larger than 1 during the LHBomb. The integration from the upper limit, t_1, corresponding to the age of formation of the lunar crust, then reduces to a simple multiplication of 3 terms:

$$\Phi(t_1) \approx K(t_1) \times \tau \times \varphi_0$$

where $K(t_1) \sim 2 \times 10^6$ is the value directly read on Fig. 4 at $t_1 \sim 4.45$ Gyr; $\tau \sim 70$ Myr a reasonable average value of the mean life of the population of impactors that rules the steepest first 200 Myr decay of $K(t)$ (Fig. 1); $\varphi_0 \sim 40,000$ tons per year (for the whole Earth) the present day micrometeorite flux measured at the Earth's orbit –it was inferred from the density of impact craters on parts of the *Long Duration Exposure Facility* (LDEF), which was exposed for about 5.8 years at an altitude of 330–480 km (Love and Brownlee, 1993).

For the Earth, this formula gives an integrated micrometeoritic flux since the formation of the Moon, $\Phi(t_1) \sim 5.6 \times 10^{24}$ g. This value is astonishingly similar to the average value ($\sim 5.2 \times 10^{24}$ g) directly inferred from the neon and nitrogen contents of micrometeorites. This striking fit is still hard to believe. Even Pierre Dac would have argued that lunar impact craters, neon, nitrogen and water (that he disliked) do not have the same origins.

10.5 An Astonishingly Good Fit Between Predictions and Observations

Total amounts of micrometeorite volatiles. The accretion formula shows that 90% and 99% of the total micrometeorite flux was delivered during the first 100 Myr and 200 Myr, respectively, of the post-lunar period of the late heavy bombardment (LHBomb). Table 2 reveals an unexpected good fit (i.e., within a factor 2) between the observations (column 2) and the corresponding predictions (column 3) of these total amounts, with the possible exception of H_2O, which might be depleted by a factor of about 2–3 (Maurette et al. 2001a, 2004a).

This fit is surprising considering:

- the uncertainties attached to the determination of $K(t_1) \times \tau$;
- the very long extrapolation back in time, beyond 3.9 Gyr ago, in a kind of blind zone where lunar cratering rates could not be measured (due to the saturation of the lunar surface with impact craters);
- The huge differences in the contents of neon, nitrogen and water in AMMs, with neon being ~100,000 and ~10 million times less abundant than nitrogen and water, respectively;

Table 2. Total amounts of volatile species in the Earth's atmosphere

$M_A \sim [A(\%)/100] \times 5.6 \times 10^{24}$ g		
Volatiles	*Observed Values*	*EMMA* (M_A)
Ne	6.5×10^{16}g	11.2×10^{16}g
N_2	4×10^{21}g	3.6×10^{21}g
H_2O	$1{,}4 \times 10^{24}$g	0.6×10^{24}g
CO_z (as carbonates)	$0{,}75 \times 10^{24}$g	1.1×10^{24}g

– The enormous differences between the mass ($\sim$2 $\times$ 10^{24} g) and age of the Earth's atmosphere formed $\sim$4.4 Gyr ago (Ozima and Podosek, 2002; Sarda et al., 1985) and the few milligram puff of atmosphere that would be released during the degassing upon atmospheric entry of about 500 contemporary AMMs;
– The very different origins of these volatiles. Solar neon was implanted in micrometeorites during their flight time to the Earth (see Sect. 19) over the last few 100,000 years. On the other hand, nitrogen and water were mostly locked in the carbonaceous component and the hydrous silicates of micrometeorites, respectively, which were formed in different zones of the solar nebula, up to 4.5 Gyr ago.

Such huge differences suggest that even in the case of water the misfit by a factor 2–3 between predictions and observations might not be sufficient to conclude that there is an excess of SMOW water in the present day oceans (see Sect. 28.5). In planetology and astrophysics, when going so far back in time, a misfit between predictions and observations within a factor 2–3 can hardly be considered significant. Further work is required to establish the reality of this depletion. But we have still trouble believing that the other fits can be so good. In particular, Hartmann constantly warns in his talks that lunar cratering rates are known within a factor 10 beyond about 4 Gyr ago, and Tolstikhin and Marty (1998) even quote a factor of 100!

All these unexpected fits between predictions and observations support the scenario, EMMA, which predict that $\sim$90% of the atmosphere was formed over a time interval of $\sim$100 Myr, during the steepest part of K(t), just after the formation of the Moon by the impact of the last planetary embryo. This scavenging impact prepared a new niche for a post-lunar atmosphere, which was mostly delivered by a long duration "storm" of early micrometeorites with a composition astonishingly similar to that of AMMs. They were probably released in the interplanetary medium during the degassing of periodic and new comets in the inner solar system (see Sect. 22).

This silent storm induced a diffuse volcanism falling from the thermosphere, which injected both gases and micrometeoric *smoke* particles in all underlying atmospheric layers, through which they slowly gravitationally settle. This new type of soft volcanism falling from the sky, and homogenously spreading to the whole Earth was involved in several "classical" mysteries of our distant past that we next try to decrypt in this book. In particular, in Sect. 18, we predict the fate of a highly refractory micrometeoritic element (iridium) in the very different environment of the Earth's upper mantle, with the major objective to further check the validity of EMMA.

10.6 Controversies about Pre-atmospheric Solar Neon and Nitrogen in Micrometeorites

These controversies are fully discussed in Sects. 19 and 29.6 for neon and nitrogen, respectively. We just outline below the neon problem. Everybody agrees that solar neon trapped in micrometeorites results from their implantation in both the low energy ($\sim$1 keV/amu) solar wind neon (SW-Ne) and the much more energetic SEP-Ne ($\geq$1 MeV/amu) carried by solar energetic particles (SEPs). But it is still argued that SW-Ne now observed in unmelted AMMs has been preferentially degassed upon atmospheric entry, because it is implanted at a much shallower depth (50 nm) than SEP-Ne, which penetrates up to a depth of about 10 μm. During a random walk to the surface activated by frictional heating upon atmospheric entry, SW-Ne is much more readily lost than the deeply shielded SEP-Ne. Therefore, the values of the concentrations of neon measured in AMMs would be lower limits, which underestimate the total amount of micrometeorite neon delivered to the atmosphere. Moreover, the partial loss of the SW component with a high initial $^{20}Ne/^{22}Ne$ ratio of 13.8 would shift the pre-atmospheric ratio stored in AMMs toward the much lower value SEP value (11.2).

This conventional view, which is widespread, is just inherited from *common sense*. However, while preparing in 1999 our first paper on EMMA, we realized that it is plainly wrong! But we never dared to publish a paper supporting our deductions mainly based on a SW simulation experiment conducted about 20 years ago (Borgesen et al., 1986). After facing last December the comments of a reviewer that was requiring that we took into consideration this obsolete view, we decided to add a new section to this book as to fully disregard it (Sect. 19.3)

In brief, the conventional random walk view faces a major problem. The SW-Ne flux in space is about 10^5times larger than that of SEP-Ne, while the concentration of SW-Ne in AMMs is about 3 times smaller than that of SEP-Ne –this is deduced from the 20/22 ratios measured in the SW, the SEPs and AMMs, of about 13.8, 11.2 and 11.8, respectively. Therefore about 99.999% of the SW-Ne incident on micrometeorites during their flight time to the Earth was lost. If it was lost in the atmosphere, its content should be rather similar to that of nitrogen, i.e., about 10^5 times higher than today. Where is this huge amount of neon, which is not in the air that we breath anymore? We show that the characteristics of solar neon now locked in unmelted AMMs, which include both its bulk concentration and isotopic composition, were mostly acquired during their flight times to the Earth ($\Delta\sim$ 200,000 yr) and not upon atmospheric entry. They were shaped during a severe reprocessing of the top layer ("skin") of micrometeorites during their exposure to a very high destructive fluence of SW-He ($\sim 2 \times 10^{19}$ He/cm^2).

The destruction of the surface occurred in tens of successive "blister-erosion" steps, through the formation of He-bubbles that blistered the surface up to the point where it flaked off to space. This blistering occurred as soon as the fluence of SW-He reached a critical threshold of $\sim 5 \times 10^{17}$ He/cm^2 corresponding to about one SW-He atom per target atom. Then a fresh surface started to be sunburned again, etc. This severely limited the concentration of all SW species, including Ne, to a very small saturation concentration. It likely represents the last "spike" of SW-Ne with the longest ranges, which ended up being shielded below the boundary between the heavily radiation-damaged surface that flakes off to space and the underlying still-crystalline substrate, right into the storage zone of SEP-Ne!

Simultaneously, SW-Ne lost its identity (i.e., its high 20/22 ratio) while being mixed to SEP-Ne. Therefore, upon heating, even the scholar random walk process would predict that both components should be released at about the same temperature! This prediction well matches the neon release pattern of an aliquot of ~ 200 AMMs observed by Nakamura and Takaoka, (2000) during a stepped pyrolysis performed between 400°C and the melting temperature of 1700°C. Consequently, the 20/22 ratio could hardly be significantly altered upon atmospheric entry in micrometeorites that were sufficiently shielded from frictional heating as to survive unmelted at the first place. More surprisingly, we also show that this conclusion also extends to the bulk concentration of neon in micrometeorites. Therefore, the characteristics of solar neon measured in unmelted micrometeorites still support the micrometeorite purity of the atmosphere. The missing SW-Ne has been found. It just got lost in space before atmospheric entry while SEP-Ne was still steadily accumulating, until the last minute of the flight times of micrometeorites to the Earth.

11 The Mysterious Fate of Early Micrometeoritic Oxygen

It is generally assumed that oxygen appeared much later in the history of the Earth, during the (Great Oxidation Event), GOE which lasted about 150 Myr, about 2 Gyr ago. But the causes of the GOE are still debated. For a long time, it was thought that it resulted from the biogenic activity of photosynthetic early life forms, which decomposed a fraction of the atmospheric CO_2 to extract the carbon necessary to their growth. But Holland (2002) now argues that it might be associated with complex changes in the composition of volcanic gases! The fate of the fraction oxygen resulting from the photodissociation of micrometeoric water vapour in the early thermosphere, during the peak of the PHBomb, was not decrypted, yet. The unsolved problem is to trace back its reaction network with early materials.

In the diffuse micrometeoritic volcanism water and other volatile species are gradually "erupting from the sky", essentially from the thermosphere. In this zone, water can be easily photodissociated by solar EUV to give reactive OH radicals. The recombination of a fraction of these radicals into water should produce a flux of nascent oxygen. It is difficult to predict the quantities of oxygen thus released and its major effects. But we can at least assess the total amount of water which was photodissociated during the peak of the LHBomb, requiring that the hydrodynamical escape of hydrogen, which triggers in turn the preferential loss of ^{20}Ne to space, decreased the ^{20}/Ne/^{22}Ne ratio from the micrometeoritic solar value ($\sim$11.8) to the atmospheric value of 9.8 (see Sect.22). Ozima kindly got for us an estimate of 10–20%. Assuming that all OH radicals recombined into water, we obtain a partial pressure of oxygen of about 2 bars, a value $\sim$10 times higher than the present day value.

In astrobiology it is important to predict the evolution of this nascent oxygen, and to evaluate its lifetime in the early atmosphere of the Earth, Mars and Venus. But one should get a better understanding of the various reaction networks which could consume oxygen. In conventional volcanisms oxygen and water percolate slowly in rocks from the mantle and the crust where they are partially consumed during the oxidation and hydration of various species and/or minerals (Kasting and Ackerman, 1968; Holland, 2002). But in the new type of micrometeoritic volcanism the trapping of oxygen would be more difficult. During its slow gravitational settling this element would encounter oxidized (CO_2, H_2O) or relatively inert (N_2) species. The processes

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of oxidation, which were probably effective on the early Earth to consume this ”nascent” oxygen, have still to be clearly identified.

We remind that all other models are based on the observation of a sharp increase in the oxygen partial pressure, which was ignited much later on (e.g., between about 2.3–2.1 Gyr ago). This sharp transition is clearly delineated in particular by the lack or formation of uraninite deposits and/or banded iron formations (BIFs) older than about 2.3 Gyr, which require the presence of a high residual partial pressure of oxygen in the atmosphere. The isotopic composition of carbon in carbonates associated with BIFs show that the partial pressure of oxygen during this period was between about 12 and 20 times the present-day value for a period of about 150 Myr. Then it decayed to the present-day value. The sharp burst of oxygen during the spectacular GOE, which has still to be clearly explained, will keep busy for years to come most investigators in this field.

But it is the much earlier burst, and not the later burst of the GOE, which would have been playing a decisive role, if life did really appear several times during this period (see Sect. 12.2). For example, oxygen is required for the synthesis of complex organics necessary to life, such as cholesterol. But its presence in water can destroy other important molecules such as sugars! Thus the composition of any prebiotic soup would be extremely dependant on the partial pressure of this element in the atmosphere and consequently in water. But nobody could tell us yet about an optimum concentration level of oxygen in prebiotic chemistry. One constraint is its present day partial pressure, which is not hindering the development of life. Another constraint is the existence of approxmately 3.5 Gyr old formations of stromatolites representing the fossilized colonies of blue-green algae. They contain cholesterol in their cell membranes, and needed oxygen to stay alive.

The fate of this early oxygen also deals with one of the major objectives of two spectacular space missions, Darwin and “Terrestrial Planet Finder”, (TPF) which were proposed by ESA (European Space Agency) and NASA, respectively (Léger, 2001). This objective is to detect oxygen and ozone in the atmosphere of extra solar system planets, with the purpose of using them as markers of life. But a contamination of oxygen formed during the accretion of hydrous interplanetary dust by planets, which probably exist in these systems, would be a challenge for the mission, if this accretion was a long-lasting phenomenon. This possibility is strengthened by the observation of extended disks of dust around Sun-like stars, which decline with time over an unexpectedly long duration of about 100–500 Myr (Greaves, 2005).

Part IV

Exobiology with Unmelted Micrometeorites

12 The Birth of Life on the Early Earth

Exobiology is a multidisciplinary science that deals with the origin and early evolution of life. For the birth of life to occur, the setting of its cosmic cradle has to be right. The first step is to make early seas and to buildup a benign greenhouse effect that prevents their freezing and/or boiling. Next, an efficient prebiotic chemistry has to operate in this water to synthesize the key macromolecules that could start dividing, thus giving the first sketch of life. This synthesis requires: energy; liquid water; salts like phosphate; organic molecules such as amino acids; mineral surfaces behaving like catalysts of their reaction; etc.

This part of the book gives an outline of the evolution of major ideas about the prebiotic chemistry of life, and discusses the contributions of micrometeorites that survive unmelted upon atmospheric entry to this chemistry. They are assimilated to microscopic chemical reactors that start functioning as soon as they are in contact with water either in the gaseous or liquid state. The next part completes this study while showing that the ashes of micrometeorites that get destroyed upon atmospheric entry (i.e., through melting or volatilization), also opened new reaction channels in prebiotic chemistry. Moreover, they probably contributed to controlling the post-lunar gentle greenhouse effect, which allowed the birth of life (c.f., Sect. 17). The major objective of parts IV and V is to argue that micrometeorites, either "dead or alive", gave the widest range of processes to synthesize prebiotic molecules. Therefore, their accretion should have played some role in the origin of life on the Earth, and possibly on Mars and many planets orbiting other Suns, because the formation and accretion of interplanetary dust is an unavoidable by-product of planetary formation.

All these contributions of micrometeorites to exobiology should be considered plausible. There was not human witness to tell us what the early Earth was like during the period of the late heavy bombardment just after the formation of the Moon by a giant Mars-sized body. Furthermore, these contributions are only supported by back of the envelope computations (they already yield worthy constraints) and/or simulation experiments in the laboratory, which are all imperfect. These comments apply to all scenarios proposed since the pioneering work of Oparin, about 80 years ago.

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12.1 The Pioneers

Graciela Matrajt (2001) gave a good summary of the evolution of early ideas about the origin of life. Let us just remember that in the middle of the 19th century, Berzelius (1834) and Wöhler and Hornes (1859) demonstrated the existence of organics in the Alais and Kaba carbonaceous chondrites. Next, Chamberlin (1908, 1911) relied on these discoveries to propose that the impact of planetesimals with the Earth could have delivered organics, which could have further reacted at the time of the impact to synthesize more complex organics.

Oparin-Haldane. In 1924, Oparin published a theory on the origin of life *("Proiskhozhdenie zhizny")*, which was reported in an English translation (Oparin, 1967) in the book of Bernal (1967). In this paper (*The Origin of Life*), which has been considered to represent the first modern view about the origin of life, the key biogenic elements (C, H, O, and N) synthesized organics in an ordered fashion. First, carbides, and especially iron carbide, which are the most stable compounds of carbon at high temperatures, are formed. Next, these reacted with an atmosphere composed of water and oxygen. Their reactions with water synthesized unsaturated hydrocarbons. A fraction of them were fully oxidized and generated CO_2. Another fraction was partially oxidized yielding CO and hydrocarbons carrying oxygen, such as aldehydes, ketones, acids and alcohols.

Nitrogen was involved in a rather similar sequence of reactions. First, nitrides were formed, which get oxidized by water vapour into ammonia, and a reaction with carbon yielded cyanogens. All these species would further react to produce complex molecules in the atmosphere. When water started to condense into early seas, these organics were dissolved to yield a prebiotic "soup" from which more complex molecules were evolving. In particular, the evolution of the dissolved substances led first to colloidal suspensions, and some of these ended up as "gels" *"floating freely in the boundless watery spaces of the oceans"*.

This concept of a prebiotic "soup" from which early life would emerge, has been widely accepted. In particular, in Sect. 16.2, we stick to the concept that reactive material formed kinds of oily films that aggregated into durable rafts and/or foams of organics that floated for long duration on the surface of the early oceans, somewhat producing a gigantic worldwide spread black tide (see epilogue).

In 1929, Haldane, who did not know about the work of Oparin, has compressed in a short essay of eight pages, entitled *"The Origin of Life"*, rather similar ideas about the origin of life, which has also been reported (Haldane, 1967) in the book of Bernal (1967). This theory is based on both a more realistic model of atmosphere (where CO_2 was replacing oxygen) and the role of UV light, which was no longer stopped by ozone, and could then synthesize organics in a mixture of water, CO_2 and ammonia. As both theories are rather similar, they are associated in the Oparin–Haldane theory.

The "organo–mineral" chemistry of life. A variety of models, still based on the concept of a prebiotic soup, were subsequently proposed. The reader is referred to the book edited by Brack (1998) to learn about them.

A favourite reaction network investigated by exobiologists –and still frequently used as a case study– is the formation of amino acids, and their polymerization into peptides (i.e., small fragments of proteins). Indeed, without these reactions there would be no life, at least as we know it. In particular, our body needs about 2000–3000 catalysts made of specific odd-shaped proteins to accelerate the chemical reactions in our cells, which otherwise would be too slow to sustain life. Furthermore, there is an apparent need for muscles, hairs and nails in humans.

Over approximately the last 40 years, many scientists have been exploiting a suggestion of Bernal (1951) in order to tackle the extreme difficulty of making such a synthesis of peptides in a homogeneous aqueous medium, where amino acids are first expected to be too much diluted. Their reaction rates would be very small in the first place. Moreover, their polymerization into peptides, which requires a loss of water molecules, would become quite problematic in a large excess of water that shifts the reaction in the reverse direction. Thus Bernal suggested that prebiotic chemistry required some "reactive" mineral surfaces, behaving simultaneously as adsorbents of molecules –which considerably increases their local concentrations– and catalysts of their reactions.

This chemistry can be coined the *organo–mineral* prebiotic chemistry of life. In previous works, the role of clay minerals (Cairns-Smith, 1966) and iron sulfides (Wächtershäuser, 1998) has been frequently stressed. We focused on ferrihydrite, which is a hydrous iron oxide that we found in micrometeorites. It might also be a component of the Martian soil (Bishop, 1998), and is found as a component of hydrothermal sources. The early hydrothermal system still represents today a credible alternative to synthesize complex organics (Holm and Anderson, 1998). However, we found that after the Moon-forming impact this system would have been quite sterile without the delivery of micrometeorite ashes such as iron sulfates and carbonates (c.f., Sect. 16.1).

Conventional wisdom considers that the origin of life occurred between about 4.2 and 3.9 Gyr ago. Indeed, prior to 4.2 Gyr ago, during the period of sterilization, the impacts of half a dozen 500 km size bodies were sufficiently frequent as to boil off the micrometeoritic oceans several times (Sleep et al., 1989). The resulting "steam" atmosphere was condensing quickly a few thousand years after the impact, thus regenerating the oceans. On the Earth, these middle-sized impactors, about 1000 times less massive that the giant Mars-sized Moon-forming impactor, could have hardly removed a noticeable fraction of the ocean water. But a lower gravity field probably allowed a much more significant loss of water on Mars (see Sect. 21.2).

This steam would have sterilized any early life forms that could develop on the Earth's surface between two successive impacts. Then, the first reliable "chemical" fossils of micro-organisms were found in approximately 3.8 Gyr old sedimentary rocks of the Isua and Akilia formations in Greenland, as carbon isotopic compositions suggestive of biochemical advanced microbial life forms (Mojszis et al., 1996) –however we heard that this work has recently been disputed, as have the fossil bacteria reported in charts.

12.2 Discontinuous "Bursts" of Early Life Prior to about 4.2 Gyr Ago?

New clues from Antarctic micrometeorites. In the early 1990s, we were newcomers in exobiology. We just followed the vogue of considering both that life did occur during the 4.2–3.9 Gyr period, and that only extraterrestrial materials surviving "intact" upon atmospheric entry could play a noticeable role in prebiotic chemistry. We thus conceived the scenario described in the next section, based on micrometeorites that survive unmelted upon atmospheric entry, and which behave as a tiny "chondritic" chemical reactors as soon as they contact liquid water or steam. Only the most recent findings obtained since our last review paper (Maurette, 1988) will be discussed. Graciela Matrajt mostly obtained them when she was associated with our group. They help further understand the functioning of such microscopic cosmic reactors, which got deposited in huge numbers on the Earth's surface during the peak of the LHBomb.

It is generally considered that life could not originate prior to about 4.2 Gyr. However, since 1999 we started to move away from this consensus, while adopting earlier views of Sleep et al. (1989). The Earth could have been continuously habitable by ecosystems that did not depend on photosynthesis, as early as around 4.4 Gyr ago, in spite of the $\sim$500 km-sized impactors.

Biological systems require an energy source. As pointed out by Sleep et al., an ecosystem where oxidants were produced inorganically (for example by the oxidation products of SO_2 that was delivered in huge amounts by micrometeorites), and not by solar light-activated photosynthesis, would have best survived the sterilizing impacts. The robustness of this deduction is further strengthened by the recent discovery that numerous families of anaerobic micro-organisms and even nano-organisms can bury themselves deeply into the terrestrial deep subsurface up to depths of about 4 to 7 km, and thrive at $\sim$113°C and pressures of 2000 bars (Uwins et al., 1998; Amy et al., 1997)! Some of the best-fitted survivors were ready to get out of their deep-seated protective niches, in order to invade the Earth's biosphere a few thousand years after each one of these sterilizing impacts, which probably lasted until about 4.2 Gyr ago.

High concentrations of micrometeoritic reactants in the prebiotic soup between the sterilizing episodes. The contribution of micrometeorites to the organo–mineral chemistry of life was probably initiated much earlier than the conventional upper limit of 4.2 Gyr, soon after the formation of the Moon, when water started to condense on a cool Earth back to 4.4 Gyr ago as indicated by the studies of detrital old zircons reported by Wilde et al. (2001).

Indeed, during the first 100 Myr that followed the formation of the Moon, the concentrations of all micrometeoritic reactants were about 10,000 times higher than 4 Gyr ago. Consequently, all the reaction networks of juvenile micrometeorites effective in the prebiotic chemistry of life were drastically accelerated. We presume that some of them, possibly very critical for the emergence of life, could have only been activated in this earlier period of high contents of reactants, during a quiet period between the few sterilizing impacts that followed the formation of the Moon.

In part V we further argue that the destruction of micrometeorites either upon atmospheric entry or during the subduction of their host oceanic plates led to the deposition of sulfates, carbonates and kerogen derivatives in the early oceans. Sulfates and carbonates fueled the early submarine hydrothermal system, which could thus have activated two of the favorite scenarios of exobiologists for the formation of prebiotic molecules in water. They are called the iron sulfide and thioester "worlds" of Wächtershäuser (1998) and De Duve (1998), respectively. Moreover, the ashes of the constituent kerogen of micrometeorites probably opened the new world of "kerogenetics" (see Sect. 16.2).

The sedimentary deposits of sulfides and carbonates were probably not fully boiled off by the ∼500 km impactors. Therefore, as soon as the steam atmosphere started to condense, all these worlds, which were somewhat dormant during the lifetime of water vapor in the atmosphere (i.e., a few thousand years), were quickly reactivated during the quiescent time interval of about 10–20 Myr between the impacts of the 500 km size sterilizing bodies.

13 Microscopic Chondritic Chemical Reactors

13.1 A Hydrous-Carbonaceous Chondritic Composition

Maurette (1998a and 1998b) gives a more detailed discussion of previous works supporting the role of unmelted micrometeorites in prebiotic chemistry. Krueger and Kissel (1987) quoted thermodynamic computations suggesting that the μm-size C-rich grains that they discovered in the tail of Halley's comet with their time-of-flight mass spectrometer on board the Vega spacecraft, when added to a prebiotic soup of organics, could trigger the formation of nucleic acids. Anders (1989) relied on the characteristics of the tiny stratospheric micrometeorites with sizes of about 5–15 μm, which amount to less than about 1% of the micrometeorite mass flux, to argue that micrometeorites played a major role in the delivery of organics to the Earth. As first quoted by Ponchelet (1989), we proposed in 1989 that much larger micrometeorites, similar to Antarctic micrometeorites, might have been functioning as individual microscopic chemical reactors on the early Earth during their interactions with gases and waters (Maurette et al., 1990, 1991b, 1998a, 1998b). Subsequently, Chyba and Sagan (1992) ceased fully supporting the role of the direct impact of comets in the delivery of such organics, and started to refer that of micrometeorites.

Antarctica micrometeorites show an abundant carbonaceous component, observable for example with:

- an x-ray microscope on line with synchrotron radiations (c.f., Fig. 4 in Maurette et al. 2003a);
- a nuclear microprobe (see Figs. 15 and 20) and;
- a transmission electron microscope (TEM) equipped with an electron energy loss spectrometer, which allows the detection of carbon and nitrogen when their concentrations are $\geq$0.1%. As observed on TEM micrographs (Fig. 25), the carbonaceous component is frequently in close contact with minerals. Some of these minerals are known to exhibit some catalytic activity in organic chemistry. They include oxides and sulfides of Fe/Ni and saponite. Saponite is closely related to montmorillonite, which is extensively used as an adsorbent and catalysts in laboratory simulation experiments of the prebiotic chemistry of life. They are both related to the important family of hydrous silicates dubbed smectites that have a poorly

M. Maurette, Microscopic Chondritic Chemical Reactors. In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 112–124 (2006)
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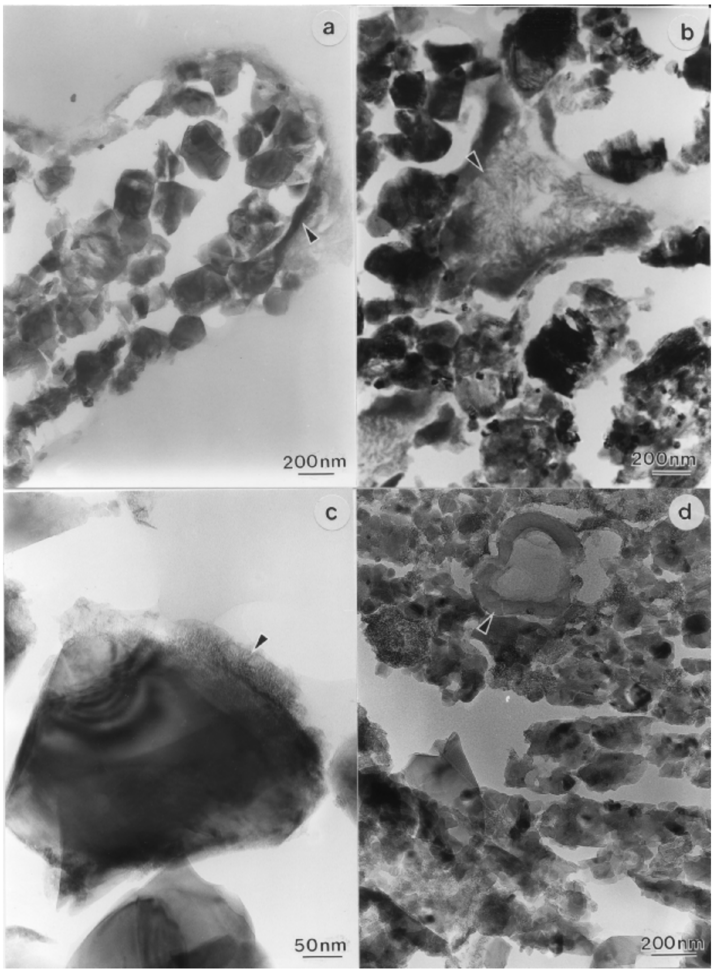

Fig. 25. Transmission electron microscope (TEM) observation of an ultramicrotomed section of a partially dehydrated scoriaceous-type Antarctic micrometeorite, which illustrates that even this type of strongly heated micrometeorites still contain a diversity of carbonaceous material. These observations were made with the 400-kV analytical transmission electron microscope of "*Laboratoire d'Etudes des Microstructures CNRS/ONERA*" (the scale bars range from 50 to 200 nanometres). The carbonaceous components were easily distinguished from the epoxy resin used to prepare this section, in particular by their different C/O ratios directly measured with the electron energy loss spectrometer of the TEM. The carbonaceous components have been classified here in four major textural groups identified with arrows, and which include: **(a)** an approximately 0.1 μm thick coating; **(b)** a large grain of ferrihydrite presenting a fibrous texture (see also Fig. 29); **(c)** an ultrathin (∼50 nanometer-thick) coating observed on the external surface of an anhydrous silicate; **(d)** small vesicles of pure organics with a size of 500 nanometers (Courtesy of C. Engrand and M. Perreau).

ordered crystalline structure, and saponite is the smectite found in extraterrestrial material.

These hydrous silicates ("clays") have a structure made of silicate sheets bridged by water molecules and cations. This structure is responsible for their catalytic properties used in the chemical industry, where montmorillonite is the most frequently used variety of smectites, even though saponite seems to be a better catalyst of the polymerization of amino acids (Bujdak and Rode, 1996). Moreover, partially dehydrated montmorillonite is even more efficient as a catalyst because the loss of water molecules between the sheets liberates adsorption sites for organics, thus increasing their local concentrations and consequently their reaction rates (J.Reisse, personnal communication).

With the present-day limit of sensitivity of the most powerful techniques of microanalyses, we could only detect a limited number of organics in micrometeorites. We first noted with the nuclear microprobe that the dominant carbonaceous component of micrometeorite and the CM chondrite Murchison is kerogen (c.f., Sect. 16.2). Furthermore a few other organics could be detected in AMMs at small concentration levels. They include:

- A rich variety of PAHs illustrated in Fig. 26, and including reactive vinyl-PAHs (Clemett et al., 1998). They are the building blocks of kerogen (i.e., PAH moieties);
- The most abundant non proteinous amino acid (AIB) previously found in CM-type chondrites was observed in AMMs by Brinton et al. (1998) with the technique of "high performance liquid chromatography". However, this finding has been challenged recently by Glavin et al. (2004). They ran new aliquots of AMMs to look for AIB that they did not detect. They thus questioned whether Brinton introduced an AIB contamination in her experimental protocol. We first note that the first step of both experiments is to extract amino acid from micrometeorites and the Murchison chondrite with liquid water at 100°C. The lack of amino acid in AMMs was contrasted with their finding in Murchison. But Murchison does not contains the nanotubes of ferrihydrite found in AMMs, in which amino acids were possibly much more strongly adsorbed and were not leached out by water in sufficient amounts as to be detected. Moreover, even though these experiments were conducted in the same laboratory, the techniques were not strictly similar. There is the important step of *acid hydrolysis* that follows hot water extraction, and that Brinton traditionally conducted in a solution of HCl at 100°C, over 24 hours. But Glavin et al. relied on a new technique where this key step is now conducted in HCl vapour at 150°C for 3 hours. So, we still do not know whether AMMs contain AIB;
- A mixture of complex organics responsible for a fluorescence observed by Raman microscopy, between about 1000 and 1300 cm^{-1} (Matrajt, 2001), which was quite similar to that observed for both CM chondrites and stratospheric micrometeorites (Wopenka, 1988). As the other carbonaceous

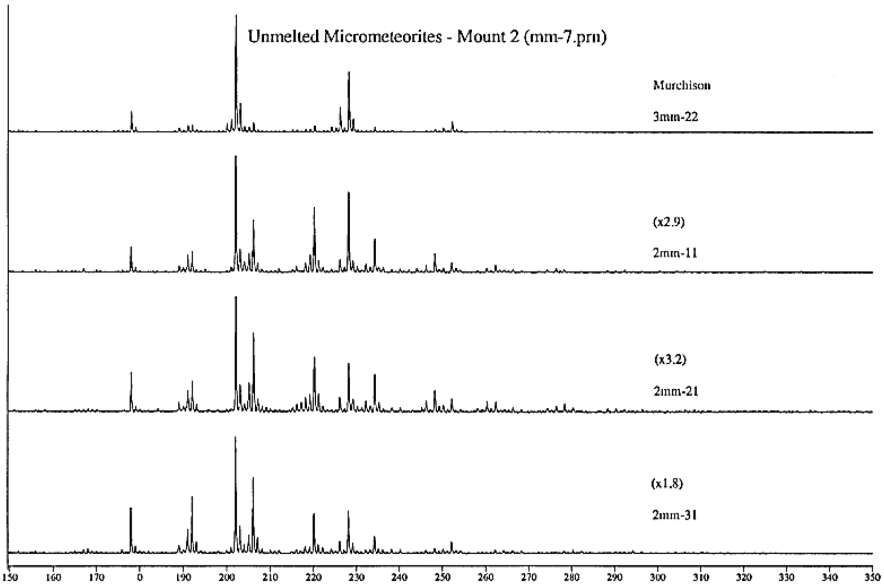

Fig. 26. Mass spectra of the polycyclic aromatic hydrocarbons softly desorbed from the CM-type Murchison and three Antarctic micrometeorites with an IR laser beam. The micrometeorite PAHs spectra, which originate from their dominant kerogen component, still bears similarities with that of Murchison that also originate from a major component of kerogen. However, the AMMs spectra looks more complex than those observed for the primitive meteorites –these spectra are further discussed by Clemett et al., (1998) and Maurette (1998b). They show in particular more side chains, including reactive vinyl-groups. In particular, the total desorption yields of PAHs are rather similar in Murchison and the AMMs, because the lower intensity of the major peak in AMMs is compensated by the larger number of peaks in their mass spectra. The PAHs spectra of typical terrestrial material such as industrial fly ashes already collected by F. Rudaux in the 1920s (see Fig. 4) would show an enormous complexity with regard to these simple spectra stored in primitive extraterrestrial materials (Courtesy of S. Clemett).

chondrites, including the CIs, yield a distinct fluorescence, this similarity further reinforces the relationship between AMMs and CM chondrites;

- The CH_2 and CH_3 constituent groups of aliphatic hydrocarbons, observed with Fourier Transform Infra red microscopy around 3000 cm^{-1} (Matrajt et al., 2001);
- Two peaks on the XANES spectra (X-ray Absorption Near Edge Structure), observed at 285 eV and 288.5 eV, and which are typical of the C–C binding of cyclic carbon, and the C=O binding of the carbonyl group, respectively (Matrajt, 2000).

There were a gigantic number of surviving micrometeorites deposited on the early Earth after the formation of the Moon. Before atmospheric entry, the equivalent thickness of micrometeorites accreted by the Earth was about 3 km around the entire surface. But upon atmospheric entry about half of this thickness was completely volatilized. The remaining half, which was forwarded to the surface, yielded a similar abundance of cosmic spherules (i.e., melted micrometeorites) and unmelted micrometeorites (both fine-grained and scoriaceous-type). Consequently, the equivalent thickness of chondritic reactors deposited on the whole early Earth's surface was only about 700 m.

About 90% of this mass was accreted during the peak of the LHBomb that lasted 100 Myr after the formation of the Moon. From these values, it can be deduced that each $1\,m^2$ spot of the Earth's surface would have accumulated about 30,000 reactors per day during the peak of the LHBomb! Therefore, these reactors could reach any spots favorable to the birth of life, even though they could have been rare on the early Earth. In particular, a lot of micrometeorites should have contained the best varieties of partially dehydrated saponite and/or nanotubes of ferrihydrite. Limitations of this scenario are related to the dominance of a chemically inert carbonaceous component called kerogen in most micrometeorites. They are more appropriately discussed in Sect. 16.2.

13.2 A Shielding within a Thin Magnetite Shell

Unexpectedly, all types of unmelted Antarctic micrometeorites are encapsulated within a $\sim 1\,\mu m$-thick protective shell (Fig. 27), which was initially characterized as being mostly made of tiny magnetite crystals. We already stressed its importance to increase the durability of the reactors –like the shell around an egg– because magnetite is one of the most durable minerals in deep-sea sediments (Maurette, 1988).

It also smooths their external surface, and consequently rules their "flight" parameters in air turbulences, as smooth particles are not as well coupled to the turbulences as irregular and fluffy particles (see Sect. 27.2). This very protective shell observed on contemporary micrometeorites was probably formed upon atmospheric entry by a still poorly understood process that possibly required an oxygenic atmosphere. In this case it would not have been formed in prebiotic conditions in the early micrometeoritic atmosphere of the early Earth, essentially composed of CO_2 and N_2 when water has condensed (i.e., similar to the present day Martian atmosphere). In this case, the concept of chondritic reactor should be abandoned. Indeed, without the magnetite shell, the millions of components of each reactor would quickly dismember in the natural environment.

Toppani and collaborators (2002, 2003) used an "atmospheric" reactor to simulate pulse heating of micrometeorites upon atmospheric entry with a minimum duration of 2 seconds. They used two distinct mixtures of gases, which were both held at a pressure of ~ 1 bar, as to simulate the compressed air "gasket" formed on the leading edge of micrometeorites upon atmospheric entry.

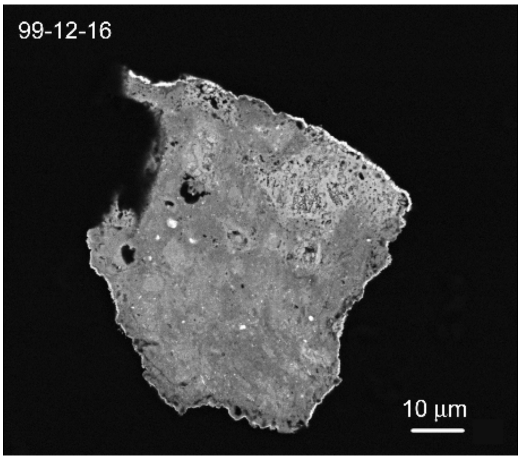

Fig. 27. SEM observation of the thin magnetic shell that increases the durability of micrometeorites (like a shell around an egg), and which appears as a thin bright rim on the polished section of the particle. As the original micrometeorite was purposely fragmented in several pieces, the rim is not continuous around the particle. This rim, which is produced upon atmospheric entry, represents a typical extraterrestrial signature of a particle even though it might not have a chondritic composition (Courtesy of C. Engrand).

The experiments were conducted in both a present-day type terrestrial oxygenic atmosphere (75% N_2 and 25% O_2) and a micrometeoritic atmosphere (95% COR_2 and 5% N_2). Fragments of the CI- and CM-type HCCs to which 99% of AMMs are related were used as analogues of micrometeorites. These experiments showed that the magnetite shell is indeed produced upon atmospheric entry in both types of atmospheres. Therefore, the magnetite protective shell of micrometeorites was formed in prebiotic conditions on both the early Earth and Mars (Fig. 28).

The characterization of the shell was also improved. They are made of a truly composite material, with magnetite crystals being imbedded into a thin glassy shell. Such a texture might induce the possible functioning of the shell as an inorganic "membrane". In fact, it would help confine a minuscule drop of prebiotic soup highly concentrated in reactants within the volume of the magnetite shell. This droplet would be in contact with a variety of minerals behaving like catalysts. This would limit the severe problem related to the dilution of the reactants encountered in all previous scenarios, including that attributing an important role to deep sea hydrothermal sources (Holm and Anderson, 1998). We next switch to one of the most interesting minerals of AMMs, ferrihydrite, which was probably involved in the organo–mineral chemistry of life.

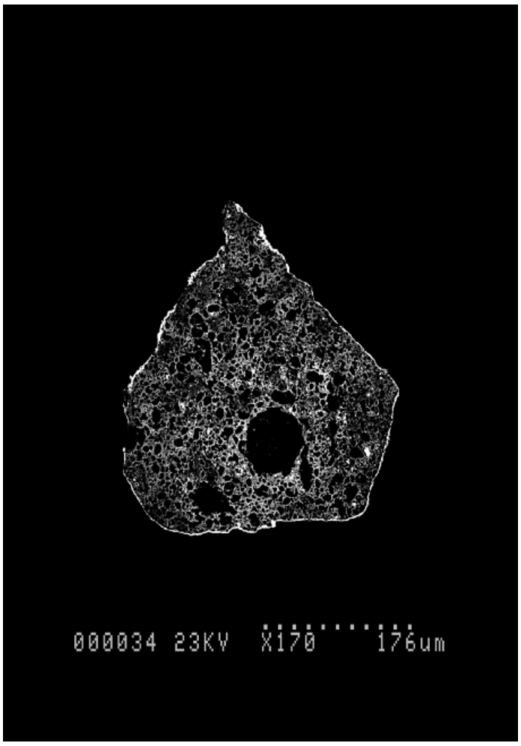

Fig. 28. SEM observation of a polished fragment of the CI-type Orgueil chondrite, which was pulse heated for 8 sec at 1350°C, in a simulated Martian atmosphere (95% CO_2 and 5% N_2. On a polished section the 1 µm thick magnetite shell is decorated by a bright approximately 1 µm thick rim of magnetite. The formation of this protective shell, which also smooths the external surface of the particles, is still not understood (Courtesy of A. Toppani).

13.3 A New "Cosmochromatograph" and Catalyst, Ferrihydrite

A "dirty" hydrous iron oxide. Among the constituent minerals of micrometeorites, Engrand and Perreau relied on electron diffraction patterns to identify a hydrous iron oxide, called ferrihydrite ($5Fe_2O_3, 9H_2O$) –c.f., Engrand (1995) and Maurette et al. (1995).

Its properties of adsorbent and catalysts in the prebiotic chemistry of life were unknown. But we were strongly intrigued by this phase because its showed:

– a peculiar fibrous texture involving hollow fibers with diameters of a few tens of nanometers that we subsequently dubbed as "nanotubes" (Fig. 29);

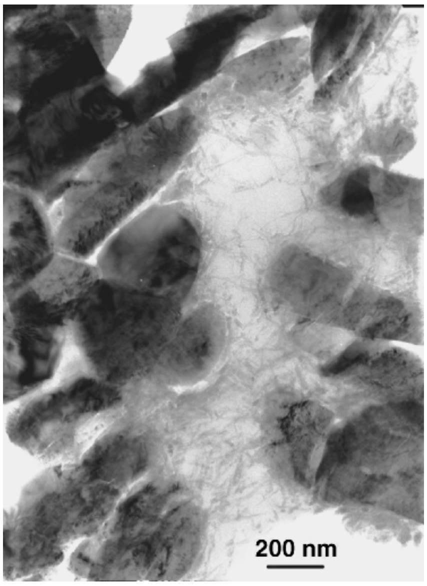

Fig. 29. Observation of an ultramicrotomed section of a Cap-Prudhomme micrometeorite with an analytical TEM. The fibrous material filling up the voids between crystals is a variety of dirty ferrihydrite probably made of nanotubes. It was identified by its characteristic electron diffraction pattern and its chemical composition as inferred with both the electron energy loss spectrometer and the X-ray spectrometer of the microscope (Courtesy of C. Engrand).

– a high concentration of all key bioelements, i.e., C, H, O, N, P, S and Cl (Fig. 30).

Then, our excitement exploded when Matrajt found that Cornell and Schwertmann (2003; see page 477) mentioned “ferrihydrite is the iron oxide with the most widespread distribution in living organisms. In the form of ferritin, an iron storage protein, it is found in all organisms from bacteria through man”. Is it possible that ferrihydrite was a basic ingredient of life, like... water?

Moreover, ferrihydrite shows an astonishing survival, as it was observed as tiny nuggets protruding outside the external surface of about 10% of the most strongly heated up and dominant family of “chondritic-barred” cosmic spherules and still capped by a magnetite rim formed upon atmospheric entry (Fig. 31, top). l. This ferrihydrite clearly originates from extraterrestrial material because it contains a specific high content of Ni (Fig. 32) never observed in rust particles found in their host Cap-Prudhomme glacial sand. Moreover, if it was formed upon the hydration of a nugget of FeNi metal and/or magnetite, then the change in volume produced by this transformation should have destroyed the “shell of the egg”, and this is not the case.

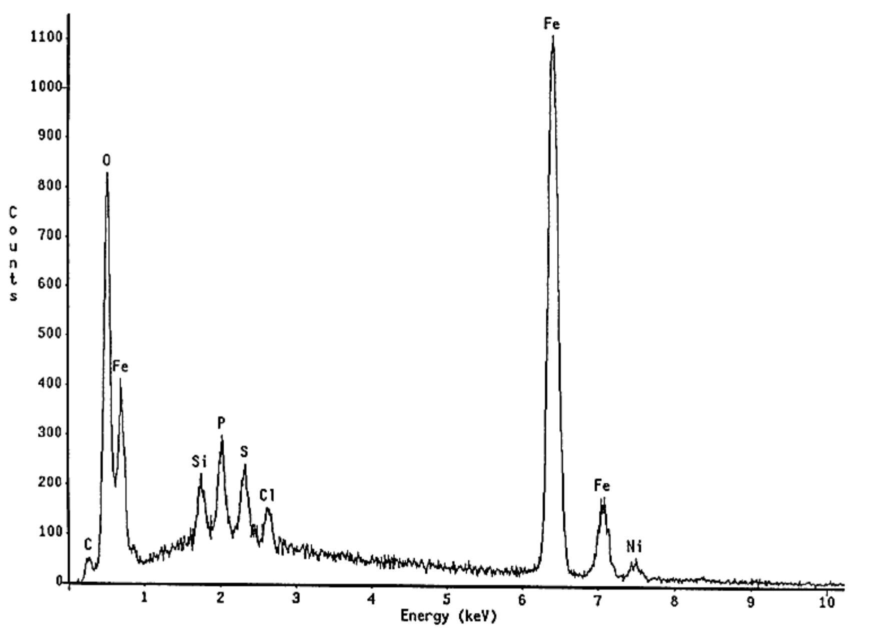

Fig. 30. Chemical composition of a ferrihydrite-rich zone of an Antarctic micrometeorite determined with the analytical TEM. This X-ray spectrum shows both a high content of Ni, which is characteristic of an extraterrestrial origin, but also the presence of other important biogenic elements such as P and S (Courtesy of G. Matrajt).

Indeed, a beautiful 1 µm-thick rim of magnetite is observed on the external surface of the nugget of the top spherule. These microscopic blobs of ferrihydrite were probably centrifuged to the external surface of the melted spherule during their fast rotation. Most of them were ejected from the melt, thus feeding micrometeoritic "smoke" particles with the ferrihydrite ashes of the "dead" micrometeorites probably capped with a magnetite shell. To make things even more puzzling, we found a micrometeorite made of pure ferrihydrite (Fig. 32).

The two reviewers of the book cautioned that ferrihydrite (that they call "rust") could have been formed by cryogenic weathering of FeNi metal and/or magnetite. However, the external magnetite rim of the nugget has not been weathered and magnetite found in micrometeorites is not as rich in Ni as ferrihydrite. However, the bottom spherule in Fig. 31, shows a kind of *flower-efflorescence* of ferrihydrite which is certainly much more complex. One of the reviewers even wrote that in this case "the picture of secondary rust should not be sold as primary ferrihydrite". In fact, one can still see underneath the microscopic flower a primary nugget still capped by a rim of magnetite." Then, this nugget probably nucleated the *rust flower*.

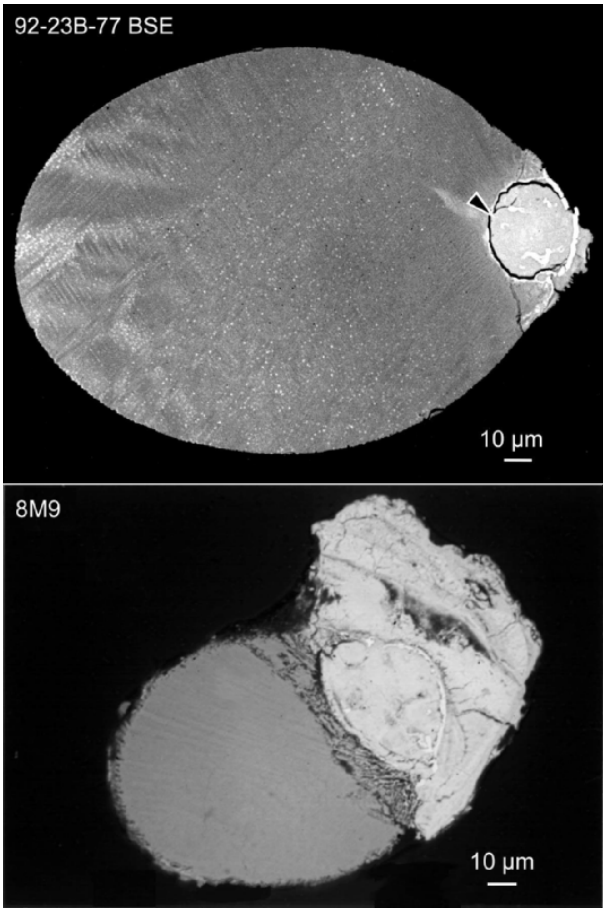

Fig. 31. SEM micrographs of polished sections of two cosmic spherules. On their right hand side both spherules show a tiny nugget of ferrihydrite protruding on the surface of the spherules, which are both coated with a thin magnetite rim. But the lower micrograph shows a much more complex ferrihydrite structure where the nugget is topped with a "flower"-looking efflorescence. The magnetite rims of the nuggets, as well as their high Ni contents, attest to their extraterrestrial origin. However, the complex flower-efflorescence observed on top of the nugget shown in the lower spherule was probably nucleated in the terrestrial environment. In this case the tiny ferrihydrite nuggets of the cosmic spherules would have considerably increased the amount of ferrihydrite available in prebiotic chemistry while giving birth to these microscopic flower efflorescences (Courtesy of C. Engrand).

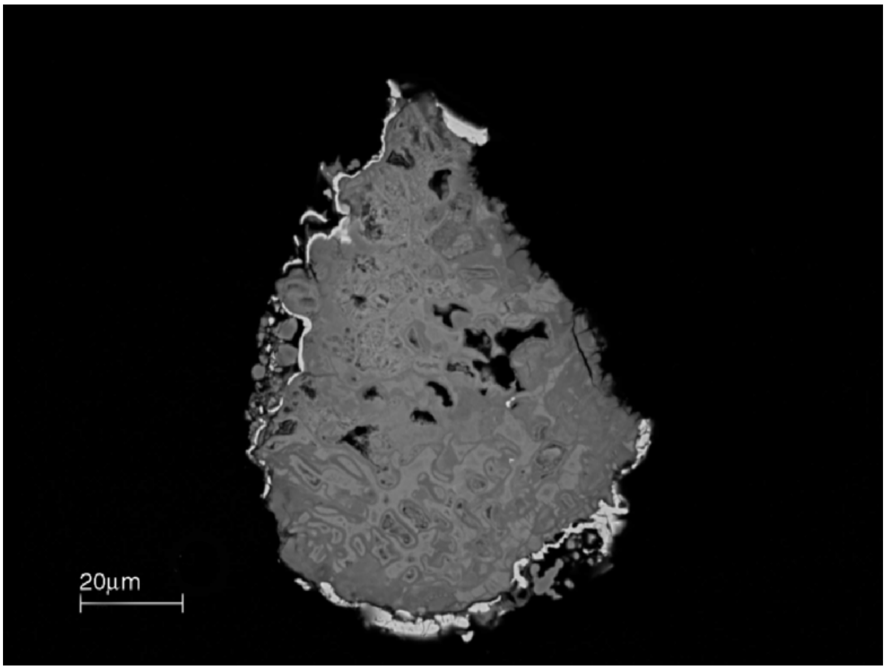

Fig. 32. SEM observation of the polished section of a broken fragment of a micrometeorite fully made of the variety of "dirty" ferrihydrite already observed within the volume of the fine-grained CP-AMMs, which shows the bright magnetite rim typical of an extraterrestrial origin (scale bar 20 µm).

In fact, for the functioning of the chondritic reactor, it is not important to know whether ferrihydrite observed in both the unmelted micrometeorites and the cosmic spherules has an extraterrestrial or a terrestrial origin. The essential feature for prebiotic chemistry is that in the case of a terrestrial origin ferrihydrite was formed very quickly after the deposition of the tiny chemical reactors on the Earth, when they where still young in order to function vigorously in the prebiotic chemistry of life, before they were exhausted and dismembered in their old age.

Therefore, we postulated that ferrihydrite could have formed microscopic centers of prebiotic chemistry, either as a component of unmelted micrometeorites or as pure nuggets reprocessed during the formation of cosmic spherules. We knew that this mineral is used as a drug to remove excess phosphates from the blood. Therefore it could have extracted at least phosphates from early seas, and probably other dissolved salts such as sulfates. We further postulated that this peculiar mineral could act as both a strong adsorbent of amino acids and a catalyst of their polymerization (Maurette, 1988b).

Chemical reactivity of small synthetic crystals of ferrihydrite. Matrajt relied on simulation experiments to assess the validity of this speculation (Matrajt et al., 2000, 2001, 2002; 2003). Large quantities (≥10 g) of ferrihydrite made of tiny crystals were synthesized, relying on several methods. The two purest varieties were identified by X-ray diffraction –as the 2-line and 6-line varieties (i.e., expressed in terms of the number of diffuse X-ray diffraction rings)– and Mössbauer spectroscopy, thanks to the cooperation of J.M. Lebreton (Université de Rennes). One sample of each variety was immersed for 24 hours at 95°C in the standard “Pierce” mixture composed of the 15 major amino acids (AAs) found in living organisms (i.e., proteinous), including negative acids (i.e., two acid and one amine group), neutral acids (one acid and one amine group) and positive acids (one acid and two amine groups).

One interesting result has been reported in Fig. 33, which gives the coefficient of adsorption of these three distinct groups of AAs in the purest “two-line” variety of ferrihydrite. This histogram shows that each AA has its own adsorption site, e.g., for a given AA the adsorption coefficient does not depend on the presence of other AAs. This is demonstrated comparing the adsorption of a few AAs of the Pierce mixture to that of the corresponding single AA in a solution. With the exception of histadine, the positive AAs yield the smallest adsorption coefficients, which are comparable to those of the two most abundant AAs observed in HCCs (isovaline and AIB), which are

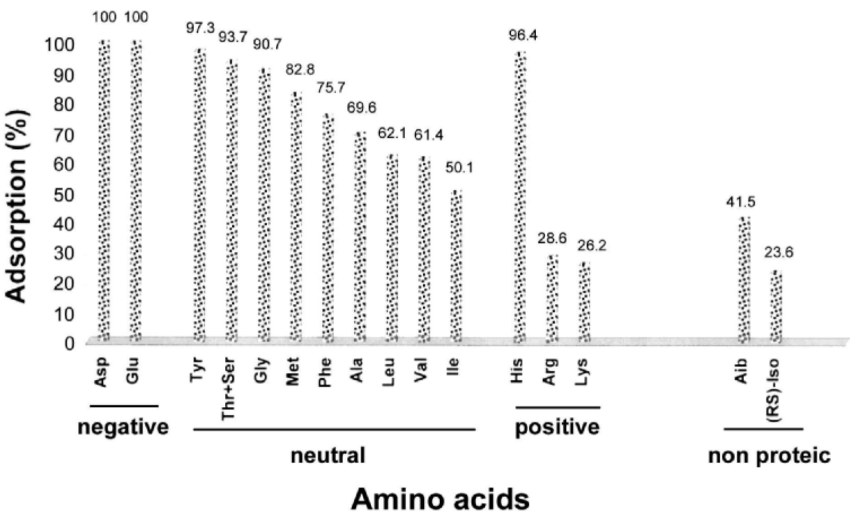

Fig. 33. Adsorption of the representative Pierce mixture of amino acids in the purest “2-lines” variety of synthetic ferrihydrite made of small crystals. The right hand side incorporates the results concerning the two most abundant amino acids found in hydrous–carbonaceous chondrites (AIB and isovaline), which are both non proteinous and neutral (Courtesy of G. Matrajt).

both non-proteinous and neutral. In the other 6-line variety, which is more ordered but contains some impurities of iron oxides, these two non-proteinous AAs are now the least adsorbed.

We thus concluded that ferrihydrite does indeed behave as a remarkable "cosmochromatograph", showing coefficients of adsorption that are much larger than those deduced for other minerals previously investigated, such as montmorillonite (e.g., Matrajt, 2002). The adsorption is remarkably high for negative acids, for which we have not noted saturation after increasing their contents by a factor of 10 in the Pierce standard –e.g., up to 0.1%. One should think about the possibility that the polymerization of the best-adsorbed negative AAs might yield unexpected peptides, which might have ruled the first steps to life.

Additional studies showed that ferrihydrite catalyzed the formation of peptide bonds without the need to activate the thermodynamics of the reactions (Matrajt et al., 2001; Matrajt 2002). However, the rates of polymerization ($\sim 10^{-4}$) still look too low to play an important role in prebiotic chemistry. But there are plausible "natural" ways to increase such rates.

An expected enhanced chemical reactivity of micrometeoritic ferrihydrite. Micrometeoritic ferrihydrite is probably much more reactive than the single crystals of the synthetic variety used to simulate its effects. Indeed, it concentrates in a small volume all major biogenic elements (C, H, O, N, P, S), as well as Fe, an important oligoelement. When ferrihydrite is imbedded into the fine-grained matrix of an unmelted micrometeorite, such bioelements are in contact on a nanoscale with important "ingredients", such as:

- minerals that have well established catalytic properties (e.g., saponite and iron sulfide);
- organics, which can be detected above detection threshold in a approximately 100 µm size grain (see Sect. 13.1);
- the mixture of complex organics still to be identified, which yield a rather similar and typical smooth raise in fluorescence observed on Raman spectra of both micrometeorites and all HCCs (Matrajt, 2002).

Another reason for the enhanced chemical reactivity of micrometeoritic ferrihydrite is related to its fibrous texture interpreted as an entanglement of "nanotubes" (Fig. 29). Their properties in the organo–mineral chemistry of life are probably quite different from those of the small 10 µm size crystals, which have been synthesized and used in the experiments of Matrajt. Therefore, we are not certain that they simulate appropriately the true characteristics of micrometeoritic ferrihydrite, which could have developed its fibrous texture upon atmospheric entry. However, the organo–mineral chemistry involving such nanotubes could be far more efficient. In particular, the huge specific area of the nanotubes should have at least drastically amplified their characteristic of adsorbency of organics and salts. They were probably implicated in a still unexplored area of prebiotic chemistry involving interactions of organics with the astonishing world of nano-materials.

14 Radiation Reprocessing of Organics by Energetic Ions in Space

In this section micrometeorites are further divided in two distinct families:

- *Most of them are delivered by the "sporadic" micrometeorite flux associated with sporadic radar and visible meteors with quasi-random directions that have a possible cometary origin (c.f., Sect. 22), which still need to be fully validated;*
- *About 2% of them are delivered by the "shower" micrometeorite flux associated with meteor showers with a well certified cometary origin. Showers are named from the constellations that lie in the direction from which they seems to originate in the sky. Thus, the Leonids and the Perseids seem to originate from the constellation of Leo and Perseus, respectively. They are produced when the Earth intersects the dusty orbits of comets Temple–Tuttle and Swift–Tuttle, respectively. The dust grains released during the sublimation of cometary ices are temporarily gravitationally bounded to these orbits in a kind of 100,000 km diameter torus, in which they are very inhomogeneously distributed as clumps, filaments, etc. Then they end up being fragmented during collisions and dispersed into the interplanetary medium. If the Earth intersects this tore there is a meteor shower to watch if one of these clumps hits the Earth.*

14.1 Reprocessing of Meteorites and Sporadic Micrometeorites

Reprocessing of meteorites in galactic cosmic rays (GCRs). For a long time we wondered why the most abundant organic in hydrous–carbonaceous meteorites and micrometeorites was a kerogen with a C/N ratio varying from about 25 to 50 (c.f., Sect. 16.2). In 2001, Jeffrey Bada suggested the possibility that the doses of ionizing radiation deposited in meteorites during their exposure age to high energy (∼1 GeV/amu) GCRs in the interplanetary medium would be sufficient to alter their initial carbonaceous matter.

Balanzat and Maurette have recently used results kindly communicated by a French group working at the GANIL accelerator (Reynaud et al., 2001), as to further assess the validity of this suggestion of Bada (Maurette et al.,

M. Maurette, Radiation Reprocessing of Organics by Energetic Ions in Space. In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 125–131 (2006)
DOI: 10.1007/10911310_14

2003c). IR spectroscopy was used to characterize radiation effects in different types of carbonaceous materials irradiated with 10 MeV/amu ions under oxygen free conditions. As soon as the ionisation dose exceeds the critical value of about 300 MGrays, all irradiated materials lose the memory of their initial properties, being converted into a "kerogen".

This confirms the deduction of Bada, and allows extending it to Antarctic micrometeorites, which dominantly originate from the sporadic flux of micrometeorites (Maurette et al., 2003b). Indeed, from the knowledge of both the fluence ($\sim$1 p/cm^2/s) and the energy ($\sim$1 GeV/amu) of GCRs, it can be deduced that the dose deposited in meteorites exceeds the critical value of 300 MGrays, when their exposure age to GCRs (GCR-ages) is larger than a few Myr. Most stony meteorites, including Martian and lunar meteorites are very dry and strongly depleted in organics at the first place. Moreover, Wieler and Craft (2001) showed that with the exception of the CI- and CM-type chondrites most of the stony meteorites have GCR-ages ranging from a few to about 70 Myr. Consequently, if they ever carried some complex organics they would have been reprocessed into kerogen. The GCR-ages of lunar meteorites are much shorter (they range from $\leq$10 kyr to $\sim$8 Myr) but they do not contain complex organics. We next discuss the cases of the Martian meteorites and the CI and CM chondrites.

Little hope for an invasion of the Earth by Martian "spores". Colleagues and science fiction writers still wonder whether early Martian "spores" and/or complex organics stored in Martian meteorites could have been seeding the early Earth, in the case where early life did develop on Mars. This possibility is unlikely.

First, the 39 Martian meteorites have flight times to the Earth bracketed between 0.6 and 18 Myr. Therefore, as life forms are certainly much more susceptible to radiation damage than the chunk of polymers investigated by Reynaud et al. (2001), most Martian meteorites would have been already fully sterilized during their exposure to GCRs. Furthermore, none of them is a regolith breccia, but differentiated rocks resulting from the cooling of a magma. Prior to their ejection to space, they suffered a regolith history on their parent asteroids (see Sect. 3.4) during which they were already exposed to sterilizing fluences of GCRs.

Their integrated time of exposure to GCRs is not available yet. However, we believe that it should be bracketed between 100 Myr and 1 Gyr, like on the Moon. This is supported by the work of Weismann (1989), which shows a striking similarities in the *crater size/crater density* distribution observed on the Moon and Mars that suggest rather similar regolith histories (see Sect. 21.2).

Complex organics were not found in the Martian soils by dedicated instruments on board the Viking spacecrafts (Biermann, 1979). It has then been suggested that oxidation related to the formation of hydrogen peroxide in the Martian atmosphere destroyed them. There is a simpler alternative. The

GCRs transformed them into evolved kerogens, which could not be detected by the Viking instruments. Indeed, Biermann clearly quotes: "Any compound that would be stable at 500°C, such as highly cross-linked polymers (i.e. evolved kerogens), would probably not produce detectable material".

One of the disturbing consequences of this deduction for exobiology is that the signature of early life forms would just be kerogens, which can only be detected in samples returned to the Earth. The trouble is that this kerogen would not be a clear-cut signature of life, because the accretion of micrometeorite in the Martian regolith would have already delivered abundant kerogens!

The exception of the CI- and CM-type chondrites. The GCR-ages of CI and CM2 chondrites mostly range between about 50 kyr and 8 Myr with a distinct cluster at 0.2–0.3 Myr. (Wieler and Graft, 2001). So, the least irradiated of these HCCs should contain a higher proportion of complex organics relative to kerogen. This might explain why the CM-type Murchison chondrite still contains a rich variety of about 400 organics at concentration levels of about 1 to 100 ppm in spite of its dominant kerogen component, which represents about 90% of the carbonaceous material.

Nevertheless, it is still hard to understand why kerogens still represent about 90% of the carbonaceous material in Murchison. In Sect. 25.4 we further discuss this wide distribution of short GCR-ages of the CIs and CMs and its astonishing similarity with the corresponding distribution measured for micrometeorites.

Reprocessing of sporadic micrometeorites (including stratospheric micrometeorites) in solar energetic particles. Solar energetic particles (SEPs) with a much smaller energy of $\sim$10 MeV/amu cannot produce any measurable cosmogenic nuclides in meteorites because their range of a few cm in rocks is too small. Consequently, their cosmogenic nuclides are lost during the ablation of the top layers of meteorites upon atmospheric entry.

But the situation is now vastly different for the 100–200 μm-sized micrometeorites sampled in Antarctica and the 5–25 μm size micrometeorites collected in the stratosphere. Indeed, their entire volume is now irradiated by SEPs nuclei. Their exposure ages in the interplanetary medium are much shorter than those of meteorites. They are spread between about a few 0.01 Myr up to a few Myr (see Sect. 22.3). But the flux ($\sim$3700 p.cm^{-2}.sec^{-1}) and the ionization energy loss rate of the SEPs with energy $\geq$1 MeV/amu are much larger than the corresponding value noted for $\sim$1 GeV/amu galactic cosmic rays. Consequently, the critical dose of $\sim$300 MGrays is reached in micrometeorites after a few 10,000 years of exposure in the interplanetary medium!

The major conclusion inferred from these estimates of radiation doses is that the constituent organics of about 98% of the meteorites (i.e., with the possible exception of some HCCs) and most of the "sporadic" micrometeorites have been severely degraded during their exposure to GCRs and SEPs, respectively. The residual material would be mostly made of a remarkably insoluble polymer kerogen (Sect. 16.2).

This challenges previous conclusions (including ours!) about the major role of the direct delivery of extraterrestrial organics to the early Earth's surface by hydrous–carbonaceous chondrites (Oro, 1961) and micrometeorites. Indeed, most of this material would only contain a very small amount of interesting molecules with regard to their dominant inert kerogens! However there are ways to skirt this pessimistic conclusion. The first one, discussed in the next section, is related to "shower" micrometeorites, deposited during meteor showers originating from comets. Moreover, another alternative is that the derivatives of micrometeoritic kerogens, which are released upon atmospheric entry, do interact with atmospheric species as to yield much more reactive species. Therefore the initial "inert" kerogens of micrometeorites would end up spicing the prebiotic soup of the early oceans with reactive organics! Even more surprising, the micrometeoritic kerogen deposited on the oceanic crust was subducted during plate tectonics as to yield kinds of cosmic petroleum (see Sect. 16.2).

14.2 Pristine Organics in Shower Micrometeorites: Beware of Analytical Techniques!

Since 1999, planetary dynamicists have developed accurate models to predict the arrival time of meteors from the Leonid shower within about 15 minutes (see Sect. 16.3). These meteors are produced by large micrometeorites, which are released from comet Temple–Tuttle –the most famous Leonid shower with a peak hourly rate of about 200,000, was observed in 1833 (Fig. 34). This accurate prediction does check the validity of these models, including their other prediction that shower meteorites are released at most a few centuries before their capture by the Earth. Consequently, their exposure to SEPs ions was too short to produce noticeable ionization radiation effects, contrarily to sporadic AMMs that originate from the "sporadic" meteor flux, exposed for a much longer duration to solar radiation, and which cannot be related to the orbit of any specific comets or asteroids.

The Leonids are not the only shower micrometeorites with a cometary origin. In fact, each year, eight much less intense regular cometary showers are occurring, which last several days at peak intensity –and not a few hours for the most intense Leonid storms occurring every 33 years or so. They include (from January to December): the Quadrantid, the Lyrid, the Eta Aquarid, the Delta Aquarid, the Perseid, the much less intense "normal" Leonid, and the Geminid. These deliver to the Earth the only pristine organics that were not transformed during their exposure to solar radiation into kerogen. It is important to assess whether their abundance relative to particles from the sporadic flux is negligible.

Fig. 34. Lithograph of the famous Leonid meteor shower of 1833 ranked at about 200,000 visible shooting stars per hour. The shadows of the observers are clearly projected on the ground. The shooting star rate during the peak of the LHbomb that lasted about 100 Myr (and not a few hours) was about 100 times higher than that observed during this intense Leonid storm.

In the historical record this abundance is determined for particles with sizes $\geq$1 mm that yield visible shooting stars, which can be counted with the naked eye in order to define the hourly rate and the duration of the shower. One next relies on the following data:

– the value of the peak intensity given as the maximum hourly rate of visible shooting stars;
– the duration of each shower at peak intensity;
– the corresponding hourly rate of about 10 measured for the sporadic flux, and effective all the year around. One finally adds to the contributions of these ordinary showers those of the much more intense Leonids storms occurring every 33.5 years. This yields an amazingly high value of their relative abundance of about 30%.

But this initial abundance has to be extrapolated to the invisible but more abundant shower particles with sizes of about 50–200 μm, which survive upon atmospheric entry. They can be deposited on the Earth's surface as the only chondritic reactors containing reactive species. This is a difficult task, in particular because one has to estimate the ratio of the flux of the small to the large particles gravitationally bound to a cometary orbit. Furthermore this ratio depends on the parent comets of the showers, and for a given comet it varies with the date of the successive returns of the comets at perihelion!

In particular, it decreases with time because there is a preferential loss of small particles through the Poynting–Roberston drag. But it might be partially compensated by the increased collisional cross sections of the large particles. We reported elsewhere a preliminary estimate of this proportion (about 2%), which has to be improved (Maurette et al., 2002). This proportion would already yield a huge amount of "shower" micrometeoritic reactors of about 100,000, per m^2, per year, during the peak of the LHBomb that lasted $\sim$100 Myr.

Therefore, the chondritic reactor scenario might have involved two distinct types of reactors:

– Reactors delivered by meteor showers that would be the only ones to contain pristine organics. With their load of potential catalysers they might have been almost self-sufficient as to function in an autonomous way as soon as they were in contact with water;
– Reactors delivered by the sporadic flux of micrometeorites, in which these reactive species were replaced by rather inert kerogens that might have impeded their functioning. Therefore, this functioning should have been fuelled by organics of the prebiotic soup, including those synthesized in the atmosphere by the derivatives of micrometeoritic kerogen liberated upon atmospheric entry (c.f., Sect. 16.2).

Anyway, we have no clues, yet, about the composition of this pristine reactive mixture of organics carried by shower particles. Consequently, we cannot decrypt its chemical reaction networks in water. This reinforces the interest of our attempts to both recover "*leonids*" from Greenland and Antarctica snow (see Sect. 22.4), even though colleagues still argue that cometary particles are preferentially destroyed upon atmospheric entry due to their higher speeds. This deduction is inferred from models that are not reliable. In particular, in Sect. 22.4 we discuss the possibility that cometary particles such as the *leonids* that impact the Earth at $\sim$70 km/sec might be as well protected as slower asteroidal particles due to the shorter duration of their pulse frictional heating.

Another major difficulty is that the techniques of microanalysis to characterize these organics in individual fragments of micrometeorites and meteorites have still to be improved. They all rely on the use of microbeams of charged particles and/or photons that either ionise and/or heat up the analysed material, where the dose of ionizing radiation can easily reach the threshold of 300 MGrays. They could thus induce the transformation of the pristine organics of shower AMMs into kerogens if they are not appropriately handled!

These analytical problems will be hopefully solved by our US colleagues, who will have to analyse precious cometary dust grains captured in the tail of comet Wild 2 (as January 2, 2004) by a collector of the Stardust Spacecraft, and which should be parachuted down next January. The exposure time of these grains in both the GCRs and SEPs was very small. Therefore, they should soon yield the first clues bout the pristine organics trapped in real cometary dust particles. But again we stress that the contribution of the chondritic chemical reactors to the prebiotic chemistry of life might have been less important than that of the reaction channels opened by micrometeorites that are destroyed upon atmospheric entry, and which generate in particular interesting ashes of kerogen! We discuss these possible contributions of "dead" micrometeorites in the next part.

Part V

Micrometeorite Ashes in Exobiology and Early Climatology

Each micrometeorite that was destroyed upon atmospheric entry during the first 100 Myr of the post-lunar period generated a high temperature wake induced during the collisions of air molecules with ablation gases. This led to high accretion rates of micrometeorite "ashes" leading to high equilibrium concentrations of smoke particles, greenhouse gases (H_2O, SO_2 and CO_2) H_2SO_4 aerosols and a variety of carbonaceous species. They built up in the upper layer of the atmosphere (thermosphere) a constantly replenished 50 km-thick dusty "cocoon" capping the whole early Earth's surface, and showing a luminescent bottom. It was probably functioning as an additional chemical reactor of prebiotic molecules, but also as a giant self-controlling heat radiator that unavoidably contributed to early climatic conditions. Micrometeoric ashes also contributed to feeding the early oceans with oligoelements required for the growth of early life forms.

15 First Hints

About 75% of the incoming micrometeorites are destroyed upon atmospheric entry, being either volatilized or transformed into dry cosmic spherules. In 1998, Cécile Engrand got the first strong hint that the ashes of these "dead" micrometeorites might also have contributed to exobiology. She found that the isotopic composition of the water "ash" that they released in the thermosphere gives the best fit to the standard SMOW value measured for an average of the terrestrial oceans (Sect. 9.2). Consequently, they contributed to exobiology, at least through the delivery of the basic fluid of life, water.

The second strong hint about this role was only found last May. It left us in a state of anxious turmoil for several weeks. We found that the new Concordia micrometeorites, which were well shielded from "cryogenic" weathering, show a very high content of sulfur (∼5%), mostly carried by iron sulfides. Upon the destruction of micrometeorites upon atmospheric entry, sulfur is first transformed into SO_2, which progressively yields sulfuric acid aerosols, like in the case of SO_2 ejected by volcanoes. The straightforward extrapolation of the accretion formula (see Sect. 10.4) yields an enormous input rate of SO_2, on par with that of water. Could it be that the early oceans were made of a concentrated solution of sulfuric acid totally inappropriate to swimming? Conventional wisdom would have fiercely shouted "IMPOSSIBLE" and quickly jailed forever EMMA in Sect. 8, entitled "*The inadequacy of previous scenarios*"!

Fortunately, André Brack rescued us, suggesting two credible ways to beneficially use this undesirable and noxious SO_2 in prebiotic chemistry, while simultaneously purifying the early oceans from their strong acidity! Later on, by using the simple model derived for iridium in Sect. 18, we even found that the subduction of the oceanic crust steadily sequestered this excess S in the primitive upper mantle in order to give a concentration of sulfur of ∼300 ppm, which fit well the average value of about 150–300 ppm reported for the upper mantle (Lorand, 1990) –c.f., Maurette 2005.

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16 Micrometeorite and Minimeteorite Ashes in Prebiotic Chemistry

16.1 High Input Rates of SO_2 and CO_2 to Feed the Early Submarine Hydrothermal System

About 80% of the Cap-Prudhomme AMMs collected near the margin of the Antarctic ice sheets showed anomalous low sulfur contents (∼0.1%) with regard to the value of ∼ 3% measured in CM chondrites, to which about 95% of these AMMs are related. We thought first, like everybody, that sulfur, which is quoted as the most volatile of the moderately volatile elements, would have been lost upon frictional heating upon atmospheric entry. But then, why is it that Ca, which is the most refractory element, would have also been lost? Moreover, there was no size effect in the loss of S and Ca going from 200 µm to 30 µm size grains. This runs against frictional heating, which increases with particle sizes. Therefore Kurat deduced that sulfur, Ca and Ni could have been preferentially lost during "cryogenic–weathering" effective in the first top meter of blue ice fields near the sea shore, involving the preferential leaching of carbonates, sulphates and sulfides (Maurette et al. 1992).

Duprat and Engrand (Duprat et al., 2003) recently recovered friable micrometeorites from snow samples deposited over the last few years in central Antarctica (Fig. 35). These particles have been well shielded from the cryogenic weathering effective in the blue ice fields of Cap-Prudhomme. Therefore, they show a much higher average sulfur content of about 5%, mostly hosted in iron sulfides (Fig. 36). Making the simple maximizing assumption that all this sulfur gets initially oxidized during atmospheric entry, like organic carbon, one ends up with an enormous initial input rate of SO_2, of about $10^{16}\,g \cdot yr^{-1}$, that lasted about 100 Myr. This SO_2 input would be even larger than that of CO_2!

This post-lunar SO_2 input was probably involved in prebiotic chemistry. First, it was quickly transformed into stratospheric sulfate aerosols (e.g., mostly H_2SO_4 molecules with ∼30% of water) that finally got deposited in early waters –this reaction scheme is well established from studies of contemporary volcanic eruptions which also release SO_2. A plausible reaction pathway to eliminate such an excess of sulfates would implicate the existence of the early submarine hydrothermal system, which probably mostly formed

M. Maurette, Micrometeorite and Minimeteorite Ashes in Prebiotic Chemistry. In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 136–151 (2006)
DOI: 10.1007/10911310_16

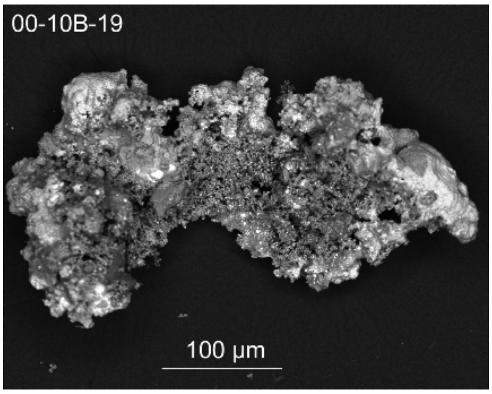

Fig. 35. SEM observation of a highly friable fine-grained unmelted Concordia micrometeorite recovered from fresh snow at a depth of about 4.5 m, near the Concordia station in central Antarctica (scale bar 10 µm), relying on a gentle collection technique, where melt snow water is just slowly gravitationally siphoned (and not pumped) through a nylon sieve with an aperture of 30 µm. This new type of micrometeorite was never before found in Antarctica (Courtesy of J. Duprat).

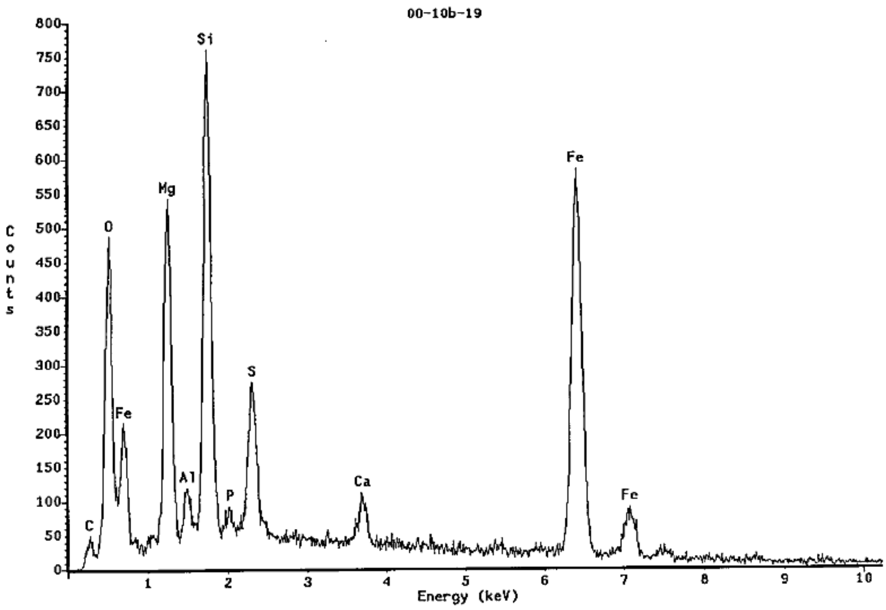

Fig. 36. Energy dispersive X-ray spectra of the bulk composition of one of the new highly friable Concordia micrometeorites. The sulfur peak corresponds to a high sulfur content of about 5% mostly carried by iron sulfides. The weaker phosphorus peak corresponds to a concentration of 0.5%. This element is probably mostly stored in ferrihydrite, one of the two only known forms of magnetic iron hydroxide, which is probably quite abundant on Mars (Courtesy of J. Duprat).

in shallow early seas (Maurette et al., 2004a). They probably functioned as "reactors", converting sulfates dissolved in water into both huge deposits of iron sulfides and exhalations of H_2S (Fouquet et al., 1996). Therefore, micrometeoritic iron sulfides volatilized upon atmospheric entry would have been converted back into terrestrial iron sulfides by this unique machinery!

This amount of reprocessed sulfides is enormous. The upper limit of their mass (about 3×10^{24} g) is equivalent to a global $\sim$500 m thick layer around the Earth. Thus, micrometeoritic iron sulfides could have intervened in prebiotic chemistry in at least two different ways. Iron sulfides are requested in the so-called iron sulfide "world" chemistry promoted by W`achstershäuser (1998). Moreover, FeS and H_2S can reduce CO_2 to organic sulfides (thiols), as demonstrated in laboratory simulation of hydrothermal synthetic reactions (Heinen and Lauwers,1996). Methyl-and ethyl-thiols were the principal thiols formed along with smaller amounts of others containing up to five carbon atoms. Thiols, during their reactions with CO_2 and H_2S, can lead to the thioesters, which probably activated important organic prebiotic chemical reactions within the thioester "world" proposed by De Duve (1998).

It is frequently suggested today that the early submarine hydrothermal system might have been functioning as a giant chemical reactor for the prebiotic chemistry of life (Holm and Anderson, 1998). However, after the Moon-forming impact, any earlier deposits of sedimentary rocks such as FeS and carbonates that resulted from the initial degassing of the Earth's interior were either blown off with the air and oceans, or scavenged to the Earth's core (FeS). Therefore, the huge post-lunar input rates of micrometeoritic H_2O, SO_2 and CO_2 were required to turn them on again. They first replenished ocean water and yielded deposits of iron sulfides and calcium carbonates, which could start fuelling again the functioning of the submarine hydrothermal system as chemical reactors.

16.2 Kerogen in Shooting Star Chemistry

Kerogens in micrometeorites and hydrous–carbonaceous chondrites. Microanalyses of both AMMs and hydrous–carbonaceous chondrites (HCCs) with a nuclear microprobe (Matrajt et al., 2001b) indicate that their major carbonaceous component is rather similar, being composed of kerogens with a C/N ratio varying from $\sim$25 to $\sim$50 –see also Sect. 6.2 and Figs. 15 and 20.

This is compatible with both:

– analysis of much larger aliquots ($\sim$500 mg) of carbonaceous chondrites, such as the CM-type Murchison chondrite, with powerful techniques of organic geochemistry such as GCMS (Cronin, 1998);
– microanalysis of micrometeorites and CM-, CI- and CV-type carbonaceous chondrites with a double laser microscope (Clemett et al. 1998). This technique revealed the mass spectra of the building bricks of kerogen, which

are polycyclic aromatic hydrocarbons called PAH-moieties (see Fig. 26 in Part IV). They were found to be related in all these types of hydrous–carbonaceous extraterrestrial materials.

Kerogens are abundant byproducts of incomplete combustion, pyrolysis and radiation reprocessing of almost any kind of precursor organics. Therefore, they are observed in a wide variety of environments, ranging from the exhaust pipes of terrestrial cars to the extraterrestrial interstellar medium and terrestrial shales.

Sylvie Derenne helped us move through the opaque jungle of kerogens. Kerogen refers to a very broad family of polymers, with C/N ratios ranging from about 20 up to 50. There are aliphatic and aromatic varieties of kerogen. Type III is made of aromatic sheets of carbon, which are bounded by other atoms. They thus look like kinds of organic analogues of clay minerals made of sheets of silicates bounded by water molecules.

In the absence of microorganisms that can digest it, kerogen is one of the most durable and insoluble organics in the natural environment. In particular it resists both strong acids and ordinary organic solvents. It was thus found that less than 10% of the organic matter of Murchison is extractable by organic solvents –more than 400 individual organics have already been found in this soluble fraction by powerful conventional techniques of organic geochemistry, including amino acids (Cronin, 1998). The acid-resistant residue of this meteorite (i.e., when most minerals have been leached out) is essentially made of kerogens with the approximate formula, $C_{100}H_{48}N_{1.8}S_2O_{12}$.

Important families of substances derive from some parent kerogen. These include petroleum, and some varieties of "activated" carbon. Activated carbon has impressive sorptive and catalytic properties. The first step in its production is to form a char from a source material, such as varieties of bitumen that derive from a precursor kerogen. Then, the resulting carbon residue is "activated" by the action of oxidizing agents such as steam and CO_2 at elevated temperatures (Cookson, 1980). Astonishingly, all these ingredients would be simultaneously generated by the initial kerogen of a fraction of the incoming micrometeorites, which will unavoidably happen to be rightly "cooked" in water vapour, SO_2 and CO_2 during their pulse heating upon atmospheric entry. Therefore, it could be that these kinds of activated byproducts of kerogen could have adsorbed organics already present in a prebiotic soup to drastically increase their concentrations and consequently their reaction rates. A pessimistic mind could also deduce that they cleaned off the oceans of their organics and consequently there was no prebiotic soup anymore!

Reprocessing of micrometeorite kerogens in a dusty thermospheric "cocoon". Micrometeorites that are destroyed upon atmospheric entry generate a kind of complex micrometeoritic "smoke" in the thermosphere. This is a mixture of very small particles, gases and ions, which is still poorly characterized as yet.

It certainly carries:

- major greenhouse gases such as H_2O, SO_2 and CO_2 that are mostly generated by the hydrous minerals, the iron sulfides and the carbonates and carbonaceous components of micrometeorites, respectively;
- hydrogenated carbon particles;
- char particles;
- PAHs–moieties resulting mostly from the degradation of their constituent kerogen;
- nuggets of ferrihydrite (see Fig. 30);
- metallic oxides;
- metallic ions such as iron, which is the dominating ion in the so-called E-layer of the thermosphere, observed around 90 km of elevation and investigated by laser sounding (Raizada et al., 2004). Even today, it is believed that they are constantly regenerated by the flux of meteoritic material.

This high elevation smoke gravitationally settles down throughout all atmospheric layers including the mesosphere, the stratosphere and the troposphere. This capability of injecting homogeneously species all over the Earth, and which will settle down through all lower atmospheric layers, is a unique feature of this micrometeoritic volcanism erupting from the thermosphere. An important fraction of the degassed water is photodissociated into oxygen and OH radicals, which generate hydrogen upon recombination (c.f., Sect. 11). Micrometeoritic smoke particles should also be exposed –for the few weeks to years of their very slow descent in the atmosphere– to other reactive species, such as SO_2, NO_x, O_3 etc.

In particular, after thermalization, most of these species could react with the hydrogenated carbon particles and the PAHs–moieties. This is expected to produce nitro-PAHs, ketones and quinines (Cookson, 1980; Schmidt, 1987), but also a variety of odd substances, including some kinds of cosmic petroleum distillates raining from the sky. Oddly enough, the initial *inert-boring-useless* micrometeoritic kerogens, which have been disregarded by exobiologists for so long, would have been converted into more reactive substances! We got further clues about this bold conjuncture while discovering the work of the Russian-Ukrainian petroleum "connection". Let us recall first about the origin of petroleum –most of the material used in the following discussion was found with the help of Google and the *Wikipedia Encyclopaedia* on the WEB.

Unexpected clues from Russia and Ukrainia. On the Earth, bitumen- and kerogen-rich shales are the source rocks of fossil fuels including petroleum (i.e., mineral oils). Like in hydrous-carbonaceous micrometeorites and micrometeorites terrestrial kerogen is insoluble in ordinary organic solvents in contrast to bitumen. There are two conflicting models about the formation of petroleum. The biogenic origin postulates that most crude oil now exploited derive from tiny plants and organisms that thrive on the top surface of the oceans (i.e., plankton). When they die they accumulate on the oceanic crust (like unmelted micrometeorites), where they are trapped in sediments that get steadily buried. At depths of a few 100 meters they are converted to kerogen. At further depths the heat and pressure breaks down kerogen to form petroleum that leaks out and can be trapped in favorable layers of porous rocks thus forming oil reserves. Most of them were formed in the Jurassic oceans, roughly at the time when the dinosaurs were thriving on Earth.

But the Russian-Ukrainian connection challenged this model since the 1860's! From their thermodynamic calculations they argue for an abiogenic origin of petroleum, which would be formed at the high pressures and temperatures produced at depths $\geq$200 km in the upper mantle. The source material was inherited from the building material of the Earth, or its reprocessing during subduction. Then, the resulting mixture of hydrocarbon did leak upward, etc.

In this model, terrestrial petroleum would be an abiogenic mixture of hydrocarbons in which bio-products have been added. As pointed out in the *Wikipedia Encyclopaedia*, after the work of the Russian geologist Nikolai Alexandrovitch Kudryavtesv, and the subsequent work of the Russian-Ukrainian connection, western geologists have now reluctantly accepted the views that abiogenic hydrocarbons exist. But they are not produced in commercially significant quantities, so that essentially all hydrocarbons that are extracted for use would be biogenic. This is what is called a brilliant consensus in science. A torrid comment to be added to this fragile consensus would be that all forms of petroleum, biogenic or not, would be daughter products of the micrometeorite kerogen present in the debris-disk Sun! Let us zoom on this bold conjuncture.

From terrestrial kerogen-rich shales to carbonaceous micrometeorites. Google took us into a stunning virtual adventure in the company of the Russian-Ukrainian connection. There are enormous reserves of bituminous and kerogen-rich shales there. But their exploitation is very costly because a lot of pollutants are released in the environment during the extraction of petroleum. So, one has still to learn how to deal with this problem.

Two simple similarities between terrestrial and micrometeorite kerogens were noted. Terrestrial shales originate from the initial mixture of clays, mud and minerals that get deposited on the floors of sedimentary basins and oceans, and which have been partially reprocessed by heat during their subsequent burial in the Earth's crust. About 90% of the micrometeorites is also made of a fine-grained matrix of clays and minerals that will be also partially "cooked" into kind of shales when unmelted micrometeorites will get deposited in buried in the same sediments. Moreover, terrestrial shales are coined as kerogen-rich rocks when they contain about 2% of kerogen. This is the value observed in micrometeorites!

To get petroleum and its derivative from a source material one relies on the classical process of fractionated distillation in stills followed by complementary distillation in vacuum stills. Then, the long chain molecules of the heavier fraction called feedstock are fed to either steam or catalytic crackers. The fraction extracted at low temperature, which is partially blended into petrol, is also a very important feedstock for making chemicals.

It can be tentatively conjectured that kerogen-rich micrometeorites that got destroyed upon atmospheric entry behaved at some point along their deceleration range as kind of particles of a kerogen-rich cosmic shale, which was subjected to a brief heating in the rarefied thermosphere at a pressure of $\sim 10^{-4}$ bar. Shooting stars might be equivalent to a gigantic number of short lived microscopic cosmic stills implanted in the thermosphere. They had a huge number of modes of functioning, as triggered by the diversity of the micrometeorite entry angles, entry speeds, masses, etc. Therefore, micrometeorites might have been delivering to the early oceans a complex mixture of *cosmic petroleum distillates* falling from the sky, and containing both soluble and insoluble species.

However, micrometeorite kerogen was not "cooked" under high pressures. Therefore, it got oxidized as to yield the CO_2 that was subsequently stored as carbonates deposits on the Earth. But like in any man made motor fuelled by petroleum derivatives the combustion is never complete. Even if only one thousandth of the initial amount of micrometeorite kerogen was transformed into a rain of petroleum derivatives that did reach the top surface of the early oceans, the lightest and probably most reactive species would have probably aggregated into some type of giant mat and/or oil emulsion, which floated for "ever" in their top surface –crude oils still leak up to the surface of the sea when wrecked tankers majestically relax on the sea bottom. If so, they could have behaved as additional chemical reactors loaded with organics, and which further adsorbed organics from the dilute prebiotic soup supporting them.

But what's about the fate of kerogen stored in unmelted micrometeorites that amount for about 25% of the incoming micrometeorite flux? Surprisingly, they should have followed an abiogenic fate that well parallels that of the organic debris of dead plankton that trigger the biogenic formation of modern petroleum. The wordings used in the previous subsection for dead plankton directly apply to unmelted micrometeorites and their major organic component, kerogen: *they accumulate on the sea floor, where they are trapped in sediments that get steadily buried. At depths larger than a few 100 meters the heat and pressure breaks down kerogens to form petroleum that might leaks and accumulate in favourable layers of porous rocks thus forming oil deposits, etc.*

But there was a major difference between the LHBomb-era and the Jurassic-era due to the much more intense impact activity prior to 4 Gyr. It unavoidably led to some giant spills of the abiogenic micrometeorite petroleum that ended up floating "forever" on the surface of the oceans, etc.

In fact, it was already observed that on the Earth petroleum accumulated around the largest impact structure (such as the ∼250 km Subdury basin in Canada) because faults can penetrate deep into the crust as to "pump" petroleum into favorable reservoirs.

We are still stuck with a kind of science fiction scenario –which are quite frequent in exobiology anyway– to reconstitute the plausible role of inert kerogen in prebiotic chemistry. A simple computation of their total amount just trapped in unmelted micrometeorites, yields an equivalent thickness of micrometeorite kerogen deposited in deep-sea sediments of about 50 m. This corresponds to a total amount of carbon carried by kerogen of about 2×10^{22} g, and about 90% of it was generated during the first 100 Myr period of the post-lunar period. For a comparison all living forms on the Earth would represent a ∼10 cm thick layer around the Earth. Furthermore, the analyses of 22 trace elements (including Ni) in the ashes of 77 varieties of petroleum correlate *significantly better* with chondritic material than with the present Earth's crust. This is indicated in a missing reference of the *Wikipedia Encyclopedia* (see reference 7, in "Abiogenic petroleum origin"). We now face the formidable challenges of understanding the meaning of "*significantly better*", and finding the missing reference!

16.3 Dreaming in Sandy Deserts about Persistent Meteor Trains in the Hadean Night Sky

The persistent trains of meteors from the Leonid showers. Most micrometeorites with sizes $\leq$500 μm decelerate today right in the thermosphere –i.e., between about 120 and 80 km of elevation. But the largest ones, with sizes exceeding a few millimeters can reach the stratosphere, where they can leave spectacular luminescent "persistent trains", which can last from a few minutes up to 30 minutes (Fig. 37).

The meteors and persistent trains of the Leonid showers have been investigated on an airborne platform of NASA by a variety of instruments during the Leonid Multi-Instrument Aircraft Campaign (c.f., Jenniskens et al., 2004). However, such a beautiful phenomena has to be observed at all magnifications, i.e., in the case of the Leonid shower, from a pair of naked eyes to powerful radar telescopes with a 300 m dish. I was lucky to observe all five Leonid showers that occurred between 1998 and 2002 with a simple pair of naked eyes carried by a pair of old shoes on the very old space platform Earth.

Seafood just before the 1998 shower. I have to shyly confess that the first campaign has no scientific rationale, but it was the cheapest one (i.e., a restaurant bill of about 120 euros). It started quite accidentally in a nice seafood restaurant in the small resort town of Le Barcares, right on the

Fig. 37. Photograph of a persistent luminescent train, which was produced near the end of the trajectory of a large particle from the Leonid meteor shower of November 2002. Such trains are the site of a peculiar glow discharge chemistry involving excited and therefore more reactive species (Courtesy of C. Marlot).

seashore of the East Mediterranean coast of France near the border with Spain.

After dinner, we had a little walk on the beach to get some fresh air. I knew about the arrival of the Leonid shower predicted for the next day during the night of the 17/18 November. But who knows? The various groups that made the predictions of their return date could not agree, and the misfit between predictions reached about 16 hours. So could they come at night about one day earlier? Therefore, I was watching over the sea surface in the Eastern direction mostly wondering whether this little walk would really help digesting the squids swimming in wine in my stomach.

Suddenly, around 11 PM, the cosmic fireworks of the Leonid shower rose up above the sea horizon as though they were fired at us. Astonishingly, it was the immense silence of this cosmic firework that impressed me the most. And I did not know how to measure the amplitude of this silence as my own pair of ears had still to be correctly calibrated (in the background of breaking waves) to make this difficult measurement. That was a dazzling unexpected show that we watched for several hours while being protected by a sand dune from a cold wind called *Tramontane*. Then the squids got digested.

Amazingly, the next morning, I had a useful complementary report by my car mechanic, who was driving exactly in the western direction opposite to the seashore, around 6 in the morning, to go to work: *Michel, I don't know what was happening. I had a fire work behind me. I was lucky that it did not reach me!* You do not need an airborne platform to conclude that it was a memorable display. Unfortunately, even my mechanic did not investigate the persistent trains of this shower, because we did not know about them. I learned a few years later that this unexpected early 1998 shower was particularly rich in very bright meteors and persistent trains, produced by cm-size particles at speed of 70 km/sec^{-1} , which have the kinetic energy of a truck moving fast on a highway!

From sand dunes to lazy lions. The following years, we started organizing (still with our own pocket money) several field trips for the naked eye. We went to Mauritania in November 1999. This was a beautiful trip for a relatively low intensity shower, with an hourly rate of visible shooting stars of about 1000 per hour, which lasted for about 3 hours at peak intensity. We estimated in particular:

- the proportion of visible shooting stars yielding a persistent trail (about 10%);
- the average size of the persistent trails (about 1–2 km);
- their maximum duration of about 15 minutes.

I have a vivid memory of the predictions of the time of the peak in the intensity of the shower, with differences between predictions reaching up to a few hours. The models were thus improved with regard to those used in 1998. Consequently, we started to watch for the shower only two days in advance. Before my departure, I had an agreement with Alessandro Morbidelli, an astronomer at the Observatory of Nice, who was interested in the Leonids. He was also my teacher in elementary planetary dynamics –I failed to get even the lowest of the elementary grade in this difficult discipline, where I was constantly attacked by confusing words such as half-life (ordinary), half-life (spontaneous), mean life, lifetimes, etc. He greatly helped in establishing contacts with some stars of this discipline, who never answered my e-mails. After the occurrence of the shower I was to call him from our campsite in the desert in order find out world winner(s) in these complex predictions. Indeed, I had a French TV team with us and they were quite anxious to have a shot of this historic phone call.

Therefore, I had to prepare well in advance to get the help of a Mauritanian geologist. He drove about 150 km of dirt road to our campsite in the desert and lent me his satellite phone. I could call Alessandro. I learnt that the winner was an obscure observatory under the unfavorable sky of Northern Ireland (don't forget, this is still in UK!), where David Asher worked with several colleagues (including Robert McNaught, another astronomer in a far distant Australian Observatory in the famous town of Coonabarabra) on the predictions of the date of the peak intensity of the shower –for a review of these works, see Asher (2000), who quotes the astonishingly good predictions of Upton, in 1977, and the work of the Russian school.

Through the magic of Internet the rightness of their prediction was quickly known and the small Irish Observatory, founded in 1790 by Archbishop Richard Robinson, became a star of the cosmic theater within a few hours after the shower. Indeed, this was the first time in the history of the Leonid shower appearances that the observed time of the peak (02:02 $\pm$ 2 minutes, AM) was so well predicted, within about 10 minutes (02:12). They were thus ahead of the next best competitors from NASA (01:48) by a comfortable margin of about 4 minutes. Soon after the success of this brilliant phone connection via communication satellites, I felt suddenly very exhausted and a bit ridiculous! What harassment for a single telephone call that was useless anyway because we started to watch the shower two days in advance! But this was the only historic phone call of my life, which was recorded by the TV team for the benefit of the future generations of *leonidicists*. It was on the air a few months after the shower.

In year 2000, I joined a team of geologists, who told me that it never rained in November on the East coast of Kenya. So the weather conditions would certainly be excellent for our observation, even though Kenya was not the most favorable choice accordingly to the predictions of a weak shower. But this was a cheap trip. The next useful information was found in a brochure on the airplane. It was clearly stated that November was one of the rainiest months in Kenya, and care should be exercised when driving a four-wheel-drive vehicle on dust roads that might be suddenly flooded by water! But it was too late to escape my wet fate.

We went to the East coast to watch over the sea surface toward the East, like in Le Barcares. Unfortunately, we had a thunderstorm and I could only see a few of the very rare most intense meteors in the narrow patches of night sky between the clouds and the lighting! Therefore, most of my trip was devoted to several wild animal watches, including that of impressively lazy lions. The dominant male was lying down on his back with legs in the air, half-bent. I felt almost asleep while being soaked up in his wild laziness.

We reconfirmed this approximate characterization of the 1999 persistent trails in November 2001, while participating in another Leonid "hunt" in the

Anza–Borrego desert, in Southwestern USA, about 150 km East from San Diego. It was organized by "*NESCORT in Exobiology*", associated with the Scripps Institution of Oceanography (La Jolla). The shower was again quite intense.

In 2002 we had our last expedition in Mauritania to observe a deceptive shower dominated by faint meteors. I could hardly mobilize my friends (including Philippe Hillary, Gero Kurat and George Slodzian) and myself to make a sustained observation of the rare persistent trains that require attention and noting. Indeed, we enjoyed too much looking for the last time at a Leonid shower knowing that the next shower would only reappear in 60 years from now. So we forgot about the science of shooting stars that possibly led to the birth of life. We had essentially a nice geological vacation under the guidance of Gero, where we explored in particular a small impact crater, the widest field of fossil stromatolites in the world, several caverns where prehistoric men made beautiful rock carvings of animals, and a potential area for future searches of a few dark meteorites. We also tried to ride on the back of camels and quite clearly my pair of eyes now carried by a camel and not by shoes was not happy. I initially thought that they could better spot dark stones from the back of a majestically slowly moving camel. However, I soon realized that the camels had to follow a broad trail in the sand, which was already full of nice desiccated camel droppings looking like small meteorites!

The overlapping of luminescent persistent trains during the LHBomb. The extrapolation of these characteristics of the Leonid persistent trains to the giant storm of early micrometeorites expected during about the first 100 Myr of the post-lunar LHBomb suggests that several trains were overlapping over a time interval of about 15 minutes in the same approximately 2 km size volume of the upper stratosphere. They thus formed a kind of a permanent and luminescent stratospheric cloud layer that lasted for about 100 Ma after the formation of the Moon, which delineated the bottom of the thermospheric cocoon by its glow.

This luminescent cirrus-type cloud, which was spread all around the early Earth, represented a type of cloud formation never produced again on the Earth over the last 4.3 Gyr. Indeed, it disappeared when the intensity of the flux of juvenile micrometeorites dropped by a factor $\sim$100, about 4.3 Gyr ago. It should have been colored because persistent trails and shooting stars show a rich palette of colors. In shooting stars they result from varying ratios of air plasma emission and metal atom emission from ablation gases ejected from the incoming meteoroids, and which are dominated by the "forest" of iron lines. The colors include red, pink (due to the first positive band emission of N_2), orange–yellow, yellow and green (c.f., next section).

This luminescent bottom of the giant micrometeoric cocoon was certainly functioning as another type of gigantic chemical reactor fed by micrometeorite ashes. Indeed, the persistent trains are known to be the site of a "glow discharge" chemistry, which is signaled by its luminescence. It leads in particular to the formation of excited and consequently more reactive species, including nitrogen. But could it synthesize useful molecules for prebiotic chemistry, such as badly needed compounds of nitrogen, sulfur and phosphorus? So far, no simulation experiment has been conducted in the regime of glow discharge on such a complex "CHONPS" early atmosphere. It could be that *nitro- sulfo-* and *phospho*-PAHs could be formed by this chemistry of excited species.

One of the important questions about this cocoon still belongs to the field of poetry: was the night looking like a day, through all these cosmic lights switched on by micrometeorites and minimeteorites being "cremated" upon atmospheric entry?

16.4 Meteors of cm-size "Minimeteorites"

Colleagues are independently working on the assumption that an efficient non-equilibrium chemistry is effective within meteors, and that it might have played a major role in the prebiotic chemistry of life –we recall that meteors are the light phenomena and/or radar echoes that decorate the atmospheric entry of interplanetary debris. Meteors are observable as shooting stars with the naked eye down to a size of a few millimeters. But below this size the micrometeoroids (micrometeorites) of the sporadic flux can still be observed as radar echoes down to an astonishingly small size of $\sim$1–10 μm (see Sect. 4.1).

These works are just summarized below, relying mostly on two papers of Jenniskens and collaborators (2000 and 2004), which were selected for four reasons:

- they are among the few concise papers on this complex topics that are enjoyable to read;
- the authors themselves have made key measurements in the meteor wakes of the recent Leonid and Perseid meteor showers on the airborne platform of NASA;
- they are very careful to state that *unfortunately, no models are yet capable of reliably handling the types of non-equilibrium chemistry implied in our observations*;
- complementary information about meteors and their role in the birth of life are soon to be given in the book of Jenniskens in preparation concerning meteors of all shapes and ages.

The observations were made with a new type of cooled CCD video spectrograph for near-infrared and visible wavelengths during the November 1998–2002 intense Leonid showers, and the 1999 Perseid shower, which occurs regularly every year in August. This instrument detected meteors five magnitude smaller than in prior photographic spectroscopic studies, i.e., down to meteoroid size of a few hundred micrometers. They studies were best made for centimetre-sized meteoroids (i.e., the incoming particle responsible for the formation of the meteors) that will be called, here in the jargon of micrometeoriticists, "minimeteorites". Smaller meteoroids (micrometeoroids) will be micrometeorites. The most important data extracted from the measurements are the temperature profiles in the wake behind the head of the meteors.

This high temperature ($\sim$4000 K) extended plasma wake can only be formed if ablation gases are ejected from the leading edge of the incoming bodies. They first form a kind of compressed gas gasket that also incorporates air molecules that collide with the gaseous species. This type of thin "skin" in front of the meteoroid, which is at temperatures of $\sim$10,000 K, amplifies its surface of collisions with air molecules. These collisions induce a process of thermalization that propagates through a cascade of collisions behind the meteoroid leading to the formation of the high-T wake at 4000 K.

Another interesting result is that the wake temperature of meteors is rather independent of the meteor magnitude (i.e., its mass) or entry velocity. These observations suggest that a non-equilibrium chemistry can occur either in the high temperature (10,000 K) meteor skin, or in the lower temperature (4,000 K) of its much more extended wake. The initial diameter and length of such wakes are about 2 m and 10 m. But this diameter expands to 100 m in less than one second, whereas the temperature sharply drops over the same time interval to $\leq$600 K. It is postulated that a fraction of the dense CO_2 early atmosphere was dissociated into CO molecules that would produce relatively high yields of potential prebiotic molecules such as a small amount of aromatic hydrocarbons and compounds rich in C=O and CN-groups. Jenniskens et al. made the comment (which is also relevant to the previous section) that *such compounds could offer numerous chemical pathways to yield other reduced molecules*. In their Table 1, they give an exhaustive listing of all compounds of this shooting star chemistry, which were reported by colleagues since 1939 (O atoms) until 2002 (Meteoritic soot).

The chemistry described for the minimeteorites should also extend to the smaller micrometeorites with sizes of $\sim$100–200 µm which deliver about 100 times more material to the Earth than all other bodies up to the size of the largest meteorites (a few meters). This is supported by the invariance of the temperature of the wake with the size and speed of the bodies that produced meteors. These ablation skins and high-T wakes thus further enrich the panoply of processes of the general "shooting star" chemistry already partially discussed in Sects. 16.2 and 16.3.

However, this chemistry was probably not very efficient about 4 Gyr ago. Indeed, the oceanic crust (and consequently the early oceans) was formed $\sim$4.4 Gyr ago. Consequently the huge amount of atmospheric CO_2 that was mostly delivered during the first 200 Myr of the post-lunar period, and which could have activated this chemistry, was dissolved in the early oceans and precipitated as carbonates. Moreover, the residual input rate of CO_2 by micrometeoroids in the thermosphere decreased accordingly to the sharp exponential decrease imprinted on the $K(t)$ curve. This input rate was about

10,000 times smaller 4 Gyr ago than 4.4 Gyr ago. Consequently, there was little dissociated CO in the atmosphere to feed a potential meteor wake chemistry.

However, the shooting star chemistry discussed in this section, as well as the functioning of unmelted micrometeorites as chemical reactors was much more efficient in earlier times. This supports the views of Sleep et al., (1989), who proposed that several bursts of life could have occurred between the impacts of ∼500 km size bodies that boiled off the oceans several times during this period (see Sect. 12.2).

16.5 Oligoelements in Precambrian Oceans

The top approximately 100 μm thick layer of the oceans, which represents their interface with the atmosphere, has recently attracted much attention. It contains enormous quantities of virus, bacteria and microscopic algae coined as phytoplankton. We only know about 10% of the bacteria and phytoplankton present in this interface, and almost nothing about marine virus. This highly biologically active layer is considered to be a kind of very important biological "filter" and/or microscopic lungs of our blue planet, which can recycle and destroy pollutants, including crude oil spills, as well as greenhouse gases, such as CO_2.

The accretion formula given in Sect. 10.2 can be applied to oligoelements, such as iron, which play a "vital" role in cell metabolism at very low concentration levels. Blain (1996) recently supported earlier views of Martin (1990), who deduced that iron plays a decisive role in the growth of phytoplankton, which produce more than 50% of the oxygen we breathe, and might regulate the exchange of CO_2 between the atmosphere and the oceans today, i.e., the modern greenhouse effect!

But the amount of this element in the oceans is amazingly small (e.g., a few 10^{-6} ppm at the centre of the Pacific Ocean). Johnson (2001) convincingly argued that the contemporary micrometeorite flux delivers about 20% of this amount. Moreover, the growth of phytoplankton today would also depend on the amount of carbonaceous material recycled by ocean-dwelling viruses and bacteria, and which contribute to feed the phytoplankton.

The elevated concentration of iron in Precambrian carbonates shows that in earlier times the concentration of iron in the oceans was much higher than today (Viezer, 1978). It is believed that this excess was due to Fe^{2+}, as present for example in a "slightly acidic solution of iron sulfates" (Blain, 1996). Astonishingly, these predictions well match the conditions expected from the interactions of early micrometeoritic SO_2 and water around 4.4–4 Gyr ago. Moreover, during the peak of the LHBomb, the flux of micrometeoritic iron was about 10^6 times higher than today, thus yielding a much larger concentration of iron in the oceans of about a few ppm. But this problem is complicated by the fact that the amount of Fe dissolved in the ocean was also dependent on the amount of free oxygen in the atmosphere, which is essentially unknown in Hadean times, yet (see Sect. 11).

Later on, in the conventional view where the first life forms appeared in the oceans, somewhere between 4.2 and 3.9 Gyr ago, the micrometeorite iron flux was still between about 1800 and 60 times higher than to day. Furthermore, the amount of the organic derivatives of micrometeoritic kerogens in micrometeoritic "smoke" was probably enormous. Did these high iron and organics contents contributed to constraining the evolution of early life forms along peculiar evolutionary paths, which triggered the preferential growth of some iron metabolising micro-organisms? They would have thrived in the top active layer of acidic early oceans, fertilised by iron and kerogen ashes "falling from the sky", and both delivered by juvenile micrometeorites.

17 Micrometeorites in the Post-lunar Greenhouse Effect

On the Earth, an astonishing balance between the absorption and scattering of solar radiation by the early Earth produced the remarkable benign greenhouse effect favourable to the origin and evolution of life. Indeed, the first constraint on any scenario is that the early oceans were not boiling or freezing! It is generally considered that the temperature has to be sufficiently high to prevent freezing at a time when the solar luminosity was smaller than today. But it has to be kept sufficiently low by some mysterious feedback effect, in order to protect the Earth from a runaway greenhouse effect, which led to a surface temperature of about 450° C on Venus. In fact, the long-lasting micrometeorite thermospheric volcanism effective after the Moon-forming impact, should have ruled the post-lunar greenhouse effect that was critical for the birth of life. Indeed, this impact eradicated at once all atmospheric ingredients of the pre-lunar greenhouse effect at a time when the young Earth was already almost fully outgassed. Subsequently, micrometeorites released simultaneously greenhouse gases for heating and smoke particles for cooling. These micrometeorite ashes resided temporarily within a kind of giant thermospheric cocoon, which might have functioned as a self-regulating IR heater during the period of low solar luminosity. Indeed, it was simultaneously heated up from the inside through the aerodynamical braking of micrometeorites.

17.1 The Major Role of the Moon-forming Impact

When was the benign greenhouse effect triggered? It is produced when the visible light from the Sun, characterized by a wavelength of about 0.5 μm, and which can penetrate throughout the clouds, reaches and heat up the Earth's surface. During the night, the heated surface cools down while emitting IR radiation. They are then absorbed by greenhouse gases, which reemit IR photons in all directions. About half of them are directed toward the Earth's surface, which continues to heat up. If a rightly-tuned cooling does not counterbalance this heating, then it runs away like on Venus, where the surface temperature reaches a scorching value of about 450°C. To defuse this cataclysm several processes have been invoked to decrease the amount of solar visible light reaching the Earth's surface.

M. Maurette, Micrometeorites in the Post-lunar Greenhouse Effect. In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 152–155 (2006)
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Since the last 20 years or so, all models have attributed a key role to the paradox of the "faint" early Sun, when the period of weak luminosity of the young Sun (by up to a factor of 30%) that lasted up to about 4 Gyr ago would have frozen the early oceans. But this cooling was counterbalanced by the effects of greenhouse gases, such as CO_2 and H_2O (Owens et al., 1979) thought to mostly originate from the degassing of the Earth's interior (Kasting, 1986, 1993).

However, the Moon-forming impact suddenly blew off all atmospheric factors that ruled the pre-lunar greenhouse effect, while allowing the accumulation of a pure micrometeoritic atmosphere. But the faint early Sun was still around. Unavoidably, micrometeorites participated in the new post-lunar greenhouse effect, which was the critical one for the origin of life.

17.2 Early Climatic Effects of the Post-lunar Thermospheric Cocoon

"Smoke" particles and greenhouse gases. The huge accretion rates of micrometeorites during the first 100 Myr period of the post-lunar period of the late heavy bombardment produced an equilibrium concentration of smoke particles, H_2SO_4 aerosols and greenhouse gases in the thermosphere. This led to the formation of a kind of giant dusty cocoon in the thermosphere with a thickness of about 50 km (i.e., corresponding to the deceleration range of micrometeorites) that homogeneously caped the whole Earth.

Let us first consider SO_2 generated during the volatilization of the constituent iron sulfide of micrometeorites. Its injection rate (number of tons, for the whole Earth, per year) in the thermosphere was roughly similar to the value estimated for water vapour and consequently about four times larger than that of CO_2. Water vapour and SO_2 are more powerful greenhouse gases than CO_2. When water has condensed, it has been shown that in a few bars CO_2 atmosphere, saturated with water vapour in equilibrium with ocean water, a small SO_2 concentration of 0.1% could already raise the surface temperature by an increment of around 20°C (Fanale, 1999). However, before its transformation into sulfates, the high injection rate of SO_2 was about four times higher than that of CO_2. This corresponds to an initial concentration of SO_2 in the thermosphere about 400 times higher than this value of 0.1%.

One can thus expect a strong heating of the Earth's surface. But it was possibly counterbalanced by the attenuation of solar light by the micrometeorite smoke particles and the H_2SO_4 aerosols of the cocoon. We discuss this problem in further detail elsewhere (Maurette, 2005). In this section we rely on back of the envelope computations and previous studies of two of the most cataclysmic historical volcanic eruptions known to man, as to give a feeling about the role of this approximately 50 km thick micrometeoritic cocoon.

Learning from historical cataclysmic volcanic eruptions. The following discussion is essentially based on the work of Rampino et al. (1988, 1992, 2000), and Thordarson and Self (1996). The eruption of Roza in British Columbia (about 14.7 Myr ago) lasted about 10 years. The Toba eruption occurred in Sumatra about 74,000 years ago and lasted approximately two weeks. The Roza eruption delivered about 6–13 $\times$ 10^{15} g of H_2SO_4 aerosols and probably 5 times as much fine dust in the stratosphere. The corresponding contributions of the Toba eruption, which is the largest known explosive volcanic event recorded yet (the energy released was about 10^4 times larger than that of the deadly Tsunami of December 26, 2004), were about 1–5 $\times$ 10^{15} g of aerosols and 10^{15} g of dust, which were injected up to heights of 27–37 km.

Rampino and collaborators investigated these eruptions in term of their climatic effects, quoted as volcanic "winters". They deduced that the Toba stratospheric dust did produce "total darkness for weeks to months". But this was a short duration event because the dust was quickly scavenged. On the other hand, the lifetime of the Toba stratospheric sulphuric aerosols was about 6 years –this was directly inferred from acidity depth profiles measurements in Greenland ice cores. Moreover, they backscattered solar radiation very efficiently. It was inferred than a stratospheric H_2SO_4 aerosol burden of about 5 $\times$ 10^{15} g would attenuate sunlight by a factor of about 10^5! Therefore, these eruptions did produced marked climatic effects.

What about the effects of the post-lunar micrometeoritic volcanism, assuming that the equilibrium concentration of micrometeoritic SO_2 and dust in the thermosphere can be reasonably approximated by their yearly input rates of about 3.8 $\times$ 10^{15} g and 2 $\times$ 10^{16} g, respectively, over the first 100 Myr of the post lunar period –only $\sim$70% of the mass fraction ($\sim$50%) of the micrometeorite flux volatilized upon atmospheric entry can yield "smoke" particles if micrometeoritic oxygen is used to oxidize both carbon and sulfur (see next section). Let us just focus on the yearly burden of H_2SO_4 aerosols of about 6×10^{15} g. The studies of the Roza and Toba eruptions suggest that the Sun was looking through the cocoon like... the full Moon... for about 100 Myr. With this kind of new faint Sun the early Earth should have been dramatically frozen.

How did our blue planet manage to rightly counterbalance this severe cooling as to allow the condensation of the oceans back to about 4.4 Gyr ago, as indicated by the dating of old Australian detrital zircons (see Sect. 23.4). It certainly involved a complex feedback still to be decrypted between dust, aerosols and strong greenhouse gases, which were constantly outpouring from the thermosphere, but also the functioning of a weak heater effective in all the volume of the cocoon. This is the frictional heating of air molecules against the leading edge of the incoming micrometeorites. A simple estimate (see, Sect. 29.4) gives an energy input rate about 250 times larger than the present day solar EUV insolation (about 1 erg cm^{-2} s^{-1}), which is mostly responsible for the current heating of the thermosphere. One should note that this value is estimated for an average speed of meteors of 15 km s^{-1}, which corresponds to the impact of asteroidal particles. But cometary dust would have higher impact speeds of about 27 km s^{-1}, and their energy input rate would be about 4000 erg cm^{-2} s^{-1}. The effects of the micrometeoritic cocoon on early climatic effects can hardly be overlooked.

Question marks about the oxygen supply. In this discussion we assumed that there was an ample supply of oxygen in the early atmosphere as to fully oxidize micrometeoritic S and C. However, the observations of a good fit between the total amount of C injected by micrometeorites and the total amount of carbonates now found on the Earth show that oxygen was indeed readily available in these earlier times at least to fully oxidize carbon. Therefore, it was very likely also available to oxidize sulfur.

But what was the source of oxygen in these earlier times? Oxygen is the most abundant material in micrometeorites (about 40 wt.%) while carbon and sulfur represent only ~2.5% and ~5% of the mass of a micrometeorites. So, there is a huge potential supply of oxygen locked in micrometeorites. But how could this oxygen mostly locked in silicates oxidize C and S initially present in kerogen and iron sulfides? We have to return to the meteor wake chemistry outlined in Sect. 16.4. In fact, the study of meteors strongly suggests that a non-equilibrium chemistry can occur both in the high temperature of the meteor "skin" of compressed gases in front of the incoming micrometeorites (10,000 K), or in the lower temperature of the much more extended wake behind the particles (4000 K). This was probably in this *skin–wake* system generated by ablation gases that micrometeoric oxygen, which was released simultaneously to C and S, could quickly oxidized both elements, when the wake was sufficiently spread in less than one second as to reach an adequate temperature.

Let us take an initial cross-section of the cylindrical wake of about 2 m × 10 m. This hot wake is formed all along the deceleration range of micrometeorites as long as ablation gases feed it, i.e., as long as the parent micrometeorite is not fully destroyed. During the first 100 Myr period of the LHBomb one can thus envision a spectacular meteor "attack" of the thermosphere. When the temperature of a wake has decreased through the diffusion of its constituent species below the temperature of dissociation of SO_2 and CO_2, it was still "spiked" by several new wakes at different temperatures over a time scale of a few seconds.

A very efficient shooting star chemistry was certainly happening in these conditions of wake "collisions" that led to the oxidation of carbon and sulfur by oxygen simultaneously delivered by micrometeorites. This oxidation scenario could even function in a pure atmosphere of nitrogen and it should extend to other reaction schemes. But this specific chemistry of colliding shooting stars, which did not last more than ~100 Myr after the formation of the Moon, still belongs to the world of plausible scenarios. We only know that carbon was fully oxidized. Thus, we believe that sulfur too was fully oxidized.

Part VI

Micrometeorites in Comparative Planetology

The validity of EMMA was first tested while predicting the characteristics and total amounts of four key volatiles in the Earth's atmosphere. The next priority was to test it a second time, looking at a very different element in a very different environment. We selected one the most refractory elements, iridium, which has also a highly siderophile character (i.e., this is an iron "loving" element which will follow the fate of iron during the formation of the Earth's core). We predicted its concentration in the Earth's mantle, getting again an astonishingly good fit between predictions and observations.

We thus built up some confidence to use this model in an orderly fashion to make predictions about the still mysterious early history of the Earth, the Moon and Mars, which are probably the best known bodies of the solar system. The model is first used to find new clues about the fate of neon on the Earth, which is one of the major long-standing problems in noble gases geochemistry. It required finding clues about the amazing "sunbursts" history of micrometeorites in the interplanetary medium, where they were implanted for a few 100,000 yr to very high destructive fluences of solar wind helium ions accelerated at speeds of around 400 km/s. Moreover, the simple observation of the micrometeoritic "purity" of the Earth's atmosphere yields new constraints about key processes effective during the early history of our blue planet, such as the functioning of the Earth's mantle.

We next move with iridium to the second best known body, the Moon, facing there the stunning problems of the "indigenous" component with a very low Ir content, which was comminuted to make lunar mare soils. Our next destination will be Mars, the third best known body, to consider the fate of another siderophile element, Ni, but also that of S, which also behaved as a strongly siderophile element on the early Earth. The early history of Mars is much less constrained than that of the Moon, but there is a spectacular *assault on Mars with the Mars-Odyssey, Mars-Express-Orbiter missions, and the Mars exploration rovers (Spirit and Opportunity). In particular the Ni and S contents of the Martian soils were measured by the APXS instruments on board both rovers (see below), and we try to predict these contents with EMMA.*

One unavoidably hits new problems when moving to unknown boundaries. One of the major objectives of this chapter is to try to convey the feeling that a decisive step in scientific investigation is not only to find credible solutions to these problems, but also to define new questions. They generally open new horizons, but because they also present new, seemingly insurmountable problems, they can cause you to consider quitting science for good! In fact, while working with Spirit and Opportunity, we got stuck with Ni and S. But, we possibly found new clues about the formation of the Martian atmosphere.

18 Micrometeoritic Iridium in the Earth's Mantle with the Hartmann Conjuncture

Prediction of iridium content. Iridium is a highly siderophile element. Accordingly to a conventional scenario (c.f., Sect. 3.5), this element was initially stored in both the planetesimals that formed the proto-Earth and the half-dozen planetary embryos (i.e., proto-planets) that subsequently merged into it. Each of these bodies, which were not fully decelerated before their impact with the Earth's surface, exploded. This led to the production of pockets of liquid silicates in which "droplets" of liquid iron nucleated. They ended up coagulating in huge metal masses that quickly sank to the core. Therefore, it can be expected that the Mars-sized Moon-forming impact, which occurred at time $t_1 \sim 4.44\,\text{Gyr}$, was scavenging any residual iridium to the core, thus preparing a new niche for the accumulation of micrometeoritic iridium.

It is likely that the Earth's oceanic crust was formed very soon after this impact (see below). In this case, micrometeoritic iridium started to accumulate on the crust since t_1. It was then delivered to the mantle through the subduction of the oceanic crust. Let us suppose that subduction was already effective at t_1. From the conjunction of the integrated micrometeorite flux since the formation of the Moon, $\Phi(t)_1 \approx 5.6 \times 10^{24} g$, and the iridium content of unmelted AMMs to be about 620 ppb (Kurat et al., 1994), the total mass of micrometeorite iridium deposited on the oceanic crust since the formation of the Moon is about 3.5×10^{18} g. It can be assumed that the efficiency of transfer of this highly refractory and siderophile element to the Earth's interior during subduction was about unity.

If micrometeoritic iridium was homogeneously distributed in the whole mantle, with a total mass of 0.7 times the Earth's mass, its average content would be 0.9 ppb. If this transfer was restricted to the upper mantle, this content increases up to about 3.2 ppb, i.e., a value surprisingly close to that quoted by Morgan (1986) for the "primitive" upper mantle ($\sim 3.4 \pm 0.3$ ppb), and which was deduced from the measurements of the Ir content of rocks from the upper mantle, such as *"spinel lherzolites"*.

The early history of the oceanic crust and Earth's mantle. The good fit observed between prediction and observations for iridium unexpectedly further comforts EMMA, and thus the conjuncture of Hartmann, which is one of its major backbones. Moreover, it yields a few additional hints about the early history of the crust and mantle of the Earth.

M. Maurette, Micrometeoritic Iridium in the Earth's Mantle with the Hartmann Conjuncture. In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 159–160 (2006)
DOI: 10.1007/10911310_18

The oceanic crust should have been formed at about the time of formation of the lunar crust, about 4.44 Gyr ago (Carlson and Lugmaier, 1988), in order to collect all the post-lunar micrometeorite contribution. This agrees with the age ($\sim$4.4 Gyr) of old terrestrial detrital zircon reported by (Wilde et al., 2001).

The mantle that extends from about 30 to 2900 km is divided into an upper and lower mantle. Their separation, which occurs at a depth of 660 km, corresponds to the endothermic transformation of olivine into perovskite. It has been argued that this transformation isolates the lower and upper mantle, which would thus function as two independent compositional convection cells (Richter, 1979). However, seismic studies would indicate that this isolation is only partial –c.f., Sotin and Parmentier (1989) for a review of previous works and Van der Hilst et al. (1997) for more recent "global" tomography evidence. Unexpectedly, micrometeoritic iridium used as a probe of convection would support the first model. Moreover, iridium either stored on the Earth before the formation of the Moon, or delivered by the Moon-forming impactor, had to be fully scavenged to the core. This supports the prediction of the model of impact scavenging outlined in Sect. 3.5.

19 Micrometeoritic Neon on the Earth

Ozima and Podosek (2002) clearly state: "In summary, there is still no satisfactory theory on the origin of terrestrial noble gases". This view is also supported by Porcelli and Pepin (2000), who note: "there still is no consensus on how the terrestrial noble gases originated". Two of the major problems with the distribution of noble gases on the Earth concern:

- *the light noble gases, with atmospheric neon showing a $^{20}Ne/^{22}Ne$ ratio of about 9.8, which is lower than in any known bulk reservoir of trapped neon in the solar system, such as rocks from the upper mantle, "gas-rich" meteorites and AMMs;*
- *xenon, which is also unique in the solar system, in showing both a peculiar mass-dependent isotopic fractionation and a marked depletion relative to Kr, which defines the mystery of the "missing" xenon. Neon in AMMs helped to tackle the neon problem while rejuvenating an earlier suggestion of geochemist, which was disregarded over the last 15 years. It also revealed that the irradiation history of micrometeorites in solar corpuscular radiations was very different from the simple regolith history experienced by both lunar dust grains and gas-rich grains in chondrites.*

19.1 Earlier Suggestions About Micrometeoritic Neon in the Earth's Mantle

The neon problem is illustrated in the compilation of analyses made by Ozima and Igarashi (2000), and reported in Fig. 38. For the sake of simplicity, we will only focus on rocks from the upper mantle called (Mid Ocean Ridge Basalts) "MORBs", which are considered as sampling the degassed upper mantle. About 60% of these rocks show $^{20}\mathrm{Ne}/^{22}\mathrm{Ne}$ ratios larger than the value of 11.2, measured in the Solar Energetic Particles ("SEPs"), which defines the "solar" zone of the plot that extends up to the solar wind ratio of 13.8 (Wieler, 1998). They yield an average value of about 11.9. Another striking observation is that the contemporary atmosphere is located near the lower margin of this cluster of data points. It is clear that early neon still trapped in the upper mantle is very different from atmospheric neon.

M. Maurette, Micrometeoritic Neon on the Earth. In: M. Maurette, Micrometeorites and the Mysteries of Our Origins, Adv. in Astrobiol. and Biogeophys., pp. 161–178 (2006)
DOI: 10.1007/10911310_19

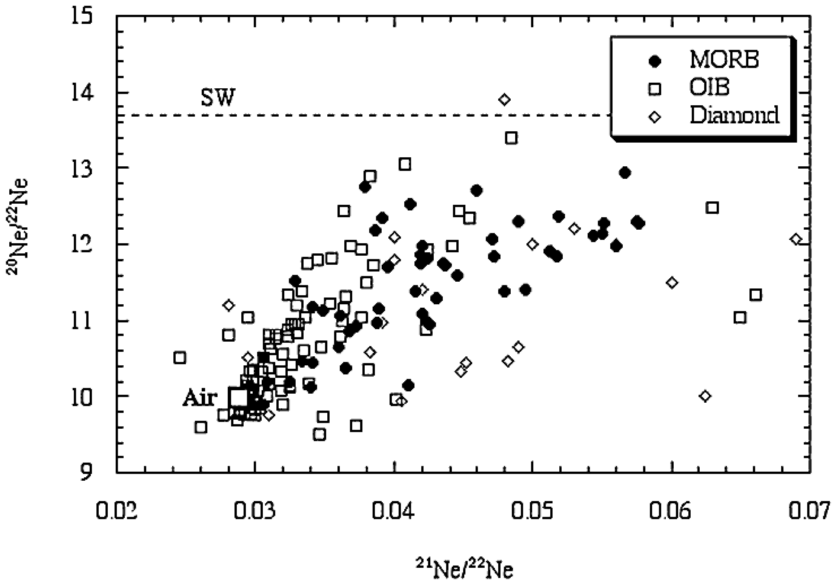

Fig. 38. Isotopic composition of neon in various rocks from the upper mantle, which is displayed on the usual three isotopes scatter plot used by geochemists. Each data point corresponds to the analysis of one rock. MORBs and OIBs refer to "Mid Ocean Ridge Basalt" and "Ocean Island Basalt", respectively (Courtesy of M. Ozima).

This finding led geochemists in the late 1980s to suggest that solar neon still present in the mantle was carried by the fraction of unmelted micrometeorites that are deposited on the oceanic crust and transferred to the mantle during subduction (Honda et al., 1987; Sarda et al., 1988; Allegre et al., 1993). This would simultaneously justify our deduction that the fraction of juvenile micrometeorites, which are destroyed upon atmospheric entry (about 75 % of the incoming flux), delivered directly the same solar neon in the atmosphere.

However, it was soon argued that micrometeoritic neon would be quickly lost during the subduction of unmelted micrometeorites. Furthermore, the earlier analyses of (Sarda et al., 1988) revealed a cluster of data points around a $^{20}Ne/^{22}Ne$ ratio of about 12, smaller than the SW value of 13.8. This could hardly be understood at a time when SEP neon was still poorly characterized. Moreover, data required to develop the simple accretion formula applicable to any element were not available. Therefore, these major criticisms could not be challenged and the model of the subduction of neon-rich micrometeorites was disregarded.

Most of the alternative models still postulate the trapping of a "solar" neon component in the mantle (Ozima and Podosek, 2002). However, it occurred at a much earlier time, during the formation of the building materials of the Earth in the early solar nebula. This neon was subsequently degassed quickly into the early atmosphere. Therefore, in both EMMA and these more "primordial" models, the initial high $^{20}Ne/^{22}Ne$ ratio of this solar atmospheric neon (generally approximated by the SW value) has to be decreased to the present-day atmospheric value of 9.8 through a preferential loss of ^{20}Ne. A popular loss mechanism, termed hydrodynamical escape (Ozima and Zahnle, 1993), is the gravitational escape of a huge amount of H_2, fed by both the dissociation of water molecules and the higher temperature of the early thermosphere related to the enhanced EUV emission of the early Sun, which dragged the excess of ^{20}Ne into space (c.f., Sect. 29.4).

We next outline the isotopic composition of neon in Antarctic micrometeorites and attempt to decipher the irradiation history of micrometeorites in solar corpuscular radiations during their flight times to the Earth. We believe that this history ruled both the content and the isotopic composition of neon measured in unmelted AMMs. This unique history is quite different from that of lunar dust grains and gas-rich grains trapped in the matrix of meteorite breccias, and where these grains get also exposed to the same radiations, but for much smaller durations, when they "jumped" on the top surface of their parent regoliths during impact gardening.

19.2 A Unique Isotopic Signature of Neon in Antarctic Micrometeorites

Micrometeorites. Nakamura and Takaoka, (2000) analyzed the isotopic composition of micrometeoritic neon in two size fractions (70–200 µm and ≤70 µm) of a glacial sand recovered at Dome Fuji, and containing about 200 micrometeorites each. These analyses show that this neon bears a unique isotopic signature made of two components (Fig. 39).

The first one is the $^{20}Ne/^{22}Ne$ ratio. The two size fractions yielded average values ranging from 11.8 to 11.9. Until now, this value, which is smaller than the SW ratio (13.8), was generally attributed to a preferential loss of SW-Ne upon atmospheric entry, because it is implanted at much shallower depths in the grains (∼50 nm) than the much more energetic SEP-Ne implanted at depths about 200 times larger. This possibility will be disregarded in the next section. We propose another alternative where this ratio would have been mainly fashioned before atmospheric entry, during the exposure of micrometeorites to very high fluences of SW-He and SW-Ne and much smaller fluence of SEP-Ne. The ratio was not significantly altered upon atmospheric entry in micrometeorites that survived unmelted at the first place..

^{21}Ne is a typical cosmogenic isotope produced during the nuclear interactions of both galactic cosmic rays (GCRs) and SEP protons with the constituent atoms of micrometeorites (see Sect. 25.3). The small $^{20}Ne/^{22}Ne$ ratio, which is the second component of the micrometeoritic neon signature, reflects a very small excess of cosmogenic ^{21}Ne (i.e., relative to ^{22}Ne) in AMMs. In

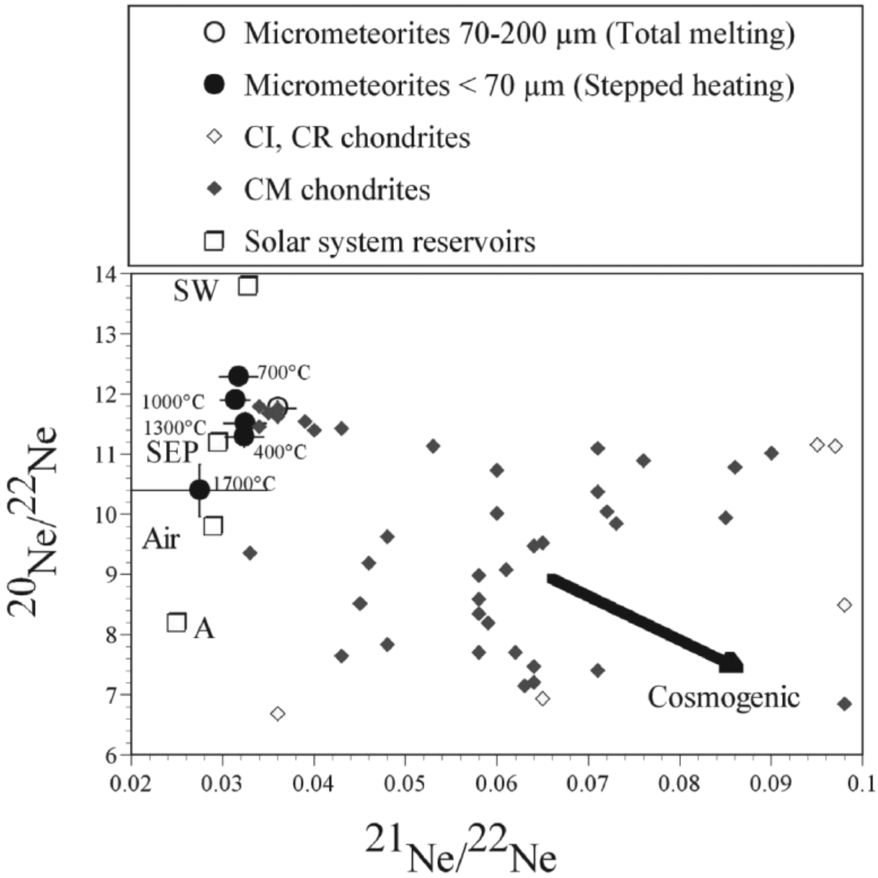

Fig. 39. Three isotope plot of the neon isotopic composition of micrometeorites (*circles*), which were recovered from two size fractions of the glacial sand collected at Dome Fuji each containing about 200 AMMs. The 70–200 µm particles were analysed by total melting at 1700°C (*open circle*), while the $\leq 70\,\mu$m particles were characterized by the powerful technique of stepped pyrolysis at 400°C, 700°C, 1300°C and 1700°C (*closed circle*). These techniques gave the most accurate average values of the $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ ratios with regard to previous determinations obtained by laser extraction from individual micrometeorites and characterized by large error bars. The bulk volume analyses of ~50 mg aliquots of CI-, CM- and CR-type HCCs (open and closed diamonds) have been reported by Tomuki Nakamura on the same plot. Most points cluster within a broad triangle that represents a three-component mixture of planetary (i.e., neon-A), solar and spallogenic gases, and which extends up to $^{21}Ne/^{22}Ne$ ratios of about 0.6 (Courtesy of T. Nakamura).

the two distinct size fractions of the Dome Fuji sand, average ratios of about 0.032 and 0.036 were measured, respectively. Their average value of about 0.034 is very close to the "primordial" value of 0.029 noted for the present day atmosphere.

This small excess of micrometeoritic ^{21}Ne is much smaller than the values either observed in Fig. 39 for bulk $\sim$50 mg samples of CI-, CM- and CR-type chondrites considered to be regolith breccias or measured in lunar samples – c.f., the similar three-isotope plot reported by Wieler (1998) for lunar sample. They all show much larger excesses of ^{21}Ne –with the exception of separates of lunar ilmenite, which does not contain the right atoms to produce measurable amounts of cosmogenic ^{21}Ne.

The excess of ^{21}Ne in lunar and asteroidal regoliths. In lunar soil samples, the ^{20}Ne/^{22}Ne ratios are bracketed between the SW to the SEP values like in AMMs. However, the lunar 21/22 ratio extends up to much larger "spallogenic" values of about 0.7. These two ratios constitute a pure signature of the reprocessing of material within a regolith. During this reprocessing, the grains experienced a complex depth trajectory in their parent regolith, due to impact gardening (see Sect. 3.4). They are exposed to protons from both the SEPs and the GCRs, when they reside up to depths of $\leq$5 cm and a few m, respectively. As their integrated residence times in the GCRs are much longer than in the SEPs, their ^{21}Ne excess is mostly due to the GCR exposure –the SEPs contribution represents a few percent at most.

The CI-, CM- and CR-types of HCCs are called gas-rich because they contain a minor component (about 10% of a the grains), which was reprocessed on the top surface of regolith before their compaction in a meteorite (see Sect. 3.4). It thus gets loaded with both solar neon and a large excess of ^{21}Ne, like lunar soil samples. However, the major gas-poor component of the meteorites does not contain solar neon, but a primordial neon (neon-A) with a much smaller ^{20}Ne/^{22}Ne of about 8. It also had initially a very small ^{21}Ne/^{22}Ne ratio of 0.026, which markedly increased when all constituent grains of meteorites were exposed "collectively" to GCRs during their flight time to the Earth. Therefore, the neon isotopic composition measured in "bulk" 50 mg samples of HCCs do not reflect any longer a simple pre-compaction regolith history of their constituent grains.

Fortunately, the association of a solar composition and a large ^{21}Ne excess, which is typical of regolith reprocessing, can be found when the minor gas-rich component of meteorites is run with a laser microprobe on a scale of about 100 μm –see Hohenberg et al. (1990) and Nakamura et al. (1999). They nicely cluster along the lunar correlation line and now constitute a reliable mark of a pre-compaction regolith history –see Wieler, 1998; his three neon isotope plot reported for mineral separates from both lunar samples and the gas-rich components of two different meteorites (Kapoeta and Fayetteville).

Therefore, AMMs can hardly originate from a material ejected from asteroidal regoliths, as sampled by gas-rich meteorites. Their high contents of solar gas are not contaminated by a component with a lower $^{20}Ne/^{22}Ne$ ratio, and their spallogenic ^{21}Ne component, which is very low, was most likely produced during their short flight times to the Earth, after their release from parent bodies "denuded" of a regolith –i.e., periodic comets, as first suggested by Raisbeck and Yiou (1989) and Osawa et al. (2000).

Mike Zolensky pointed out that the image of comet Borelli appears to show an appreciable regolith. Therefore we have to keep in mind that some (many?) periodic comets are not denuded of a regolith. However, these regoliths are short-lived as they would be destroyed during repeated returns to perihelion. Their constituent particles can hardly accumulate the large amount of ^{20}Ne observed in AMMs, lunar samples and the gas-rich zones of HCCs, with require an exposure of about 5000 yr on the top surface of any regolith.

These short flight times of micrometeorites have been deduced from their cosmogenic ^{10}Be contents. They are bracketed between about 0.05 Myr and 2 Myr (see Sect. 22.3), and they show a peak in their distribution around 200,000 years ago. As discussed in the next section (see Subsect. 9), they are quite consistent with the value independently inferred from the average ^{20}Ne content (1.5×10^{-5} cc STP/g) and $^{20}Ne/^{22}Ne$ ratio ($\sim$11.8) of AMMs. This would imply that the isotopic composition of neon in micrometeorites just *reflects the distribution of their flight time in the interplanetary medium and that it was not significantly altered upon atmospheric entry.*

19.3 The Severe Solar Wind "Sunburns" of Micrometeorites

Pre-atmospheric volatiles in AMMs. Since the writing of our first paper about EMMA, in 1999, we had to constantly improve our understanding of the pre-atmospheric characteristics of the four key volatiles used in this scenario (see Sect. 9), starting with the corresponding values measured in unmelted micrometeorites, which already best survived against frictional heating upon atmospheric entry.

For N_2, H_2O and CO_2 we were guided by the remarkable similarity between AMMs and the CM chondrites. For example, for water, in our two first papers, we quoted a water content of AMMs carried by their hydrous silicate of $\sim$4%, which was clearly smaller than the value measured for the CMs (7.7%). We thus ended up with a real deficit of water by up to a factor of 3 while injecting this value of 4% in to the accretion formula (Maurette et al., 2000a, 2000b). In fact, it could only be reliably assessed after identifying the type and the relative abundance of these hydrous minerals, and understanding their thermal degradation.

In CMs, the total abundance of major hydrous silicates (mostly serpentine and saponite) is about 20% and this yields a water content of about 7.7%. The same dominant minerals are also observed in AMMs. However, as saponite starts dehydrating at only 100 °C, the loss of water upon atmospheric entry is unavoidable. Fortunately, the dehydrated hydrous minerals can still be identified from their relict chemical composition (see Sect. 25.2). It can be deduced that the total abundance of hydrous silicates in AMMs is similar to the value observed in the CMs ($\sim$20%). But now saponite, which contains more water than serpentine, is the dominant hydrous silicate and the bulk water content of micrometeorites before atmospheric entry is slightly larger ($\sim$10%) than that of CMs –i.e., about 2.5 times higher than our earlier estimate!

However, the characteristics of Ne in AMMs are totally different from those measured in CMs! One cannot rely any longer on the strong relationship between CMs and AMMs to constrain the pre-atmospheric characteristics of solar neon in micrometeorites. Indeed, the CMs show bulk Ne contents at least 10 times lower as well as a much larger value of their 20/22 ratio, which fits the SW value (13.8) –this "pure" SW component is carried by the minor fraction of the gas-rich grains, which were exposed on the top surface of the regolith. Relating the characteristics of neon measured in AMMs to their pre-atmospheric values did require a brand new approach based on the complex physics of ion implantation effects in solids in the high fluence regime.

We thus reached the unexpected conclusion that the characteristics of the solar neon trapped in micrometeorites would have been essentially shaped during their exposure to a very high and very damaging fluence of SW-He during their long flight time to the Earth ($\sim$200,000 yr). This runs contrarily to the conventional view supported by our colleagues, who believe that these characteristics were mostly determined during a preferential loss of SW-Ne during the very short ($\sim$1 sec) terminal flash heating of AMMs upon atmospheric entry.

We never dared to demonstrate the validity of our conclusion. However, last December, a reviewer of a paper asked that we take into consideration the conventional view that we knew to be obsolete! He even required authoritatively checking our answer to his comment. We now present this answer as a rather technical section of nine pages, which was not forwarded to him because the paper was rejected by another reviewer for cause of "Panacea Universalis" (see last Subsect.)

Controversies between common sense and ion implantation physics. Solar neon in micrometeorites is found in abundance in unmelted micrometeorites after atmospheric entry. It is made of about $^1/_4$ solar wind neon (SW-Ne) with a high 20/22 ratio of 13.8, and $^3/_4$ neon from solar energetic particles (SEP-Ne) with a much lower ratio of 11.2 –these proportions are deduced from the average 20/22 ratio measured in micrometeorites ($\sim$11.8). Both components first accumulated during the flight time of micrometeorites to the Earth, $\Delta\sim 200,000$ yr, which is inferred from the peak in the distribution of their galactic cosmic ray ages deduced from their ^{10}Be content (see Sect. 22.3). Then, their abundance ratio might have been altered upon their flash heating upon atmospheric entry.

The widespread belief of colleagues as expressed by the reviewer, is that SW-Ne was severely lost upon atmospheric entry. Their simple conventional view, inherited from *common sense*, can be summarized within one paragraph. It states that low energy SW-Ne (∼1keV/amu) is implanted at a much shallower depth (50 nm) than the much more energetic ≥1MeV/amu Ne from the solar energetic particles (SEP-Ne) that penetrate at depths about 200 times larger (up to 10 µm) –these depths are scaled by the "mean projected range" of the ions along a perpendicular to the surface, R_p. Therefore, during its random walk to the surface, SW-Ne is expected to be much more readily lost than the deeply buried SEP-Ne.

In this case, the values of the concentration of neon measured in AMMs (see Table 1) are lower limits, which underestimate the total amount of neon delivered to the early Earth. Moreover, the preferential loss of the SW component with its high initial 20/22 ratio would have decreased the pre-atmospheric ratio toward the much lower SEP value of ∼11.2. –c.f., Wieler (1998), Nakamura and Takaoka, (2000). This would invalidate the concept of the micrometeorite purity of the atmosphere for neon with regard to at least the 20/22 ratio, which is further used as a probe of early solar system process in Sect. 24.2.

Common sense is very powerful because anyone can follow its logic and think themselves clever. But it is also dangerous, because it extinguishes painful meditations that are required to vaguely sense the harsh reality. In fact, these predictions are all wrong! The real problem is much trickier to decipher. Fortunately we conducted for other purposes a key solar wind simulation experiment about 20 years ago (Borgesen et al., 1986), which greatly helped invalidate this conventional view. We now take the reader on a trip of ∼200, 000 years in the interplanetary medium, to follow the severe "skin" problem of a freshly released ∼100 µm size micrometeorite, which got very sick. It was subjected to a destructive high fluence of SW-He, which peeled off its skin about 60 times!

Stunning challenges for common sense. Let me just counter the conventional view with another *common sense* deduction. The distribution of the projected ranges of the particles around R_p shows a roughly Gaussian distribution around the mean projected range, R_p. Around an energy of 1 keV/amu, about 60% and 40% of the SW-Ne ions have longer and shorter ranges, respectively and more ions move inward than backward. If the surface of micrometeorites is simultaneously eroded for a sufficient time, for example by the orthodox SW-ion sputtering, then the residual SW-Ne will be trapped in the deeper accumulation zone of the SEP-Ne. In this zone, both types of neon lose their identity and will become indistinguishable upon frictional heating through the random walk. Consequently, even though a large fraction of neon might have been lost upon frictional heating, the pre-atmospheric value of the 20/22 ratio would hardly be altered!

Even worse, the flux of SW-Ne is about 10^5 times higher than that of SEP-Ne while the implanted neon mixture found in AMMs includes only 1/4 of SW-Ne diluted in 3/4 of SEP-Ne. But we show below that SEP-Ne was not lost upon atmospheric entry. So, this would imply that about 99.999% of the SW component was lost upon atmospheric entry. This looks already quite odd remembering that during a random walk SW-Ne has as much chance to move forward as backward!

Moreover, this component would have still been delivered to the Earth's atmosphere, and the total amount of neon reported in Table 2 would be about 10^5 times larger, being on a par with that of nitrogen. The amount of oxygen per litre of gas that we breathe would be about 2 times smaller. This would be equivalent to reading this book on top of a ~6000 m high mountain without an oxygen mask. Something sounds wrong here. Where is the lost neon? Let us open this real cosmic thriller of the missing neon.

The simple SW sputtering of lunar dust grains in the low fluence regime. We found some clues about a more realistic interpretation about five years ago, when trying to understand why the formation of the 1 μm thick shell of magnetite around micrometeorites upon atmospheric entry did not induce a severe loss of their solar neon. Indeed; the high concentration of neon was similar to those already observed in the most "gas-rich" material we knew, i.e., lunar dust grains and the gas-rich grains of meteorite breccias, which were both not subjected to atmospheric entry. But in spite of these similar bulk Ne contents, their 20/22 ratios are very different. In the regolith of the Moon and the parent asteroids of gas-rich meteorites it corresponds to the SW value (~13.8). But the smaller average ratio of micrometeorites (~11.8) indicates a very different solar neon dominated by the SEP-component. What's going on here?

In previous works dealing with the effects of SW ions on lunar dust grains (see the review of Pillinger, 1979) it was argued that upon irradiation, the concentration of a given species reaches a saturation fluence, $\Phi_{s,}$ which is somewhat inversely proportional to the orthodox sputtering rate of the target expected from any beam of 1 keV/amu ions hitting a surface, and which kicks out surface atoms one by one. Approximately, $\Phi_{s,}$ has been reached when a thickness of material, R_p, has been removed. In the solar wind all ions have the same speed and consequently the same $R_p \sim 50$ nm in silicates (except hydrogen which has a range about twice larger).

Furthermore, taking into consideration the abundance of the ions in the SW, their different sputtering rates and their efficiency to induce permanent radiation damage, we deduced that SW-He is the most efficient ion in space to produce a saturation fluence (i.e., a saturation concentration) in these lunar conditions –i.e., in the low fluence regime, when the residence time of the particles on the top surface of the lunar regolith is limited to about 5000–10,000 yr (Langevin, 1978). Therefore the $\Phi_s(Ne)$ value of SW-Ne will just be obtained by multiplying $\Phi_s(He)$ by the Ne/He ratio in the solar wind of about 0.17/75.

But this does not hold for the fluence of SEP-He and SEP-Ne with energies $\geq$1 MeV, which are about 10^5 times smaller, and that penetrate much deeper into the target ($R_p \approx 10\,\mu$m in silicates). They are not affected by SW sputtering and steadily accumulate with time without reaching a saturation concentration. Furthermore, over such short exposures their concentrations of SEP-neon are much too small to be detectable in the high background of SW-Ne. This already gives a hint that the lower 20/22 ratio observed in AMMs might be due to their much longer flight times in the interplanetary medium, $\Delta \sim 200,000$ yr.

A key deuterium implantation. Indeed, for longer exposure times in the SW, this simple "low fluence" view is not valid anymore. To get new clues about pre-atmospheric neon in micrometeorites we relied on ion implantation experiments conducted about 20 years ago with a variety of ion implanters and flat targets exposed perpendicularly to an incident beam of SW-type ions. These implantations were aimed at objectives as diverse as:

– checking whether simple molecules, such H_2O, CNH and CH_4, can be synthesized in oxygen-rich lunar dust grains and/or interstellar silicates during their co-implantation with SW-type H, C and N ions (Bibring et al., 1974b);
– relating the saturation concentrations of solar wind species in lunar dust grains to radiation damage and ion sputtering (Borg et al., 1985);
– assessing water reserves of the Moon (Blandford et al., 1985);
– understanding the durability of materials to be selected in the future technologies of fusion reactors (Borgesen et al., 1986);
– assessing the long term stability of radioactive waste storage materials, as related to their in-situ irradiation by α-recoils generated during the spontaneous disintegration of actinides (Dran et al., 1980).

The most useful one was conducted with a mass spectrometer on-line with both a 30 kV accelerator for implantation and a 2.5 MV Van de Graaff accelerator for ion beam analysis. During implantations with increasing fluences of D ions we could monitor the content of D retained in the targets during their implantation with 2.5 keV/amu D ions, using the D(^{3}He,α)H nuclear reaction (Borgesen et al., 1986). The implantations were conducted up to the largest fluence of $\sim 2 \times 10^{18}$ D/cm^2 that could be achieved without "burning" the targets.

All incident D ions were trapped in the targets up to about $2{-}3 \times 10^{17}$ D/cm^2. Then, beyond this kind of "reemission" threshold, the targets got "sick" and started to reject an increasing fraction of the incoming ions. At about $1{-}2 \times 10^{18}$D/cm^2, they got so sick that they rejected all incoming D. Then, D reaches a saturation fluence, $\Phi_s(D) \approx 2{-}4 \times 10^{17}$ D/cm^2.

The remarkable feature is that this general trend is observed at *room temperature* not only in our choice of targets –i.e., a simulated lunar glass (SLG) that does not contain alkali; a soda-lime glass; olivine; oligoclase; silicon; ilmenite; sapphire– but also in targets investigated by others (silicon; graphite; silica; TiC; TiB_2). However, these solids have very different sputtering rates (i.e., olivine is sputtered ~10 times faster than ilmenite) and very different sensitivities against radiation damage. Even more amazing, this effect is well observed in metals implanted at low temperatures, when the fast diffusion of He and radiation damage defects has been quenched.

All lunar studies, in which our colleagues are still bogged down today, become immediately obsolete in the high fluence regime, where the critical parameter in building up a saturation fluence is now a threshold atomic concentration of implanted species, of about 1 atom per target atom. Moreover, some of the targets, such as the SLG, olivine and sapphire, get even sicker than the other ones. They show a kind of chaotic behaviour above $\sim 10^{18}$ D/cm^2. They never reach a clear-cut saturation concentration like ilmenite. They release a succession of erratic "spikes" of implanted species (technically termed "*the peaked structure of the retention curve*") indicative of blistering.

A new type of "SW-sunburn" erosion in the high fluence regime. Since the pioneering work of Jech and Kelly (1970), simulation experiments were conducted many times with noble gases. They were intended in particular to develop the material of the first wall of the plasma confinement vessel of fusion reactors. Indeed, very high fluences of solar wind type 3 MeV α-particles from the (D,T) fusion reaction will hit this wall (together with 14 MeV neutrons) that they will severely damage. They form in particular He-bubbles and blisters that burst to the surface of ceramics used for electrical insulation while flaking off their external layer. Furthermore, the tiny mineral inclusions, which are always found in the various metals proposed for the first wall, will be quickly sputtered to poison the plasma, quench its high temperature and shut down the reactor!

He-bubbles at high pressure form when the concentration of He in the targets exceeds about 1 *at/at* within R_p. This corresponds to a critical He fluence, $\Phi_c(He) \approx 4 \times 10^{17}$ He/cm^2, in the *flat target* case, where a flat target is continuously exposed perpendicularly to the ion beam, without knowing the day and night cycle of a real cosmic dust grain rotating in space. The molar volume of He is then equivalent to a huge pressure of $\geq$10 kbar within the bubbles. Therefore, blisters are formed, which soon flake off the surface of the target.

Insulators, known as "nuclear particle track detectors", and such as silicates, readily develop an amorphous layer of radiation damage material with a thickness $\sim R_p$ (coined amorphous "coating") upon a SW-He implantation. It starts to be observed at a fluence of about 2×10^{17} He/cm^2 on a flat target. Huge stresses build up right at the interface between the amorphous coating and the host crystalline substrate, and the diffusion of He is considerably enhanced in the amorphous material. This interface thus acts as an efficiency sink that "pumps" SW-He. This effect assists the specific "peeling" of the target "skin" at a depth R_p, when $\Phi_c(He) \geq 4 \times 10^{17}$ He/cm^2.

Troubles in the high fluence regime. Going much beyond $\Phi(He) \sim 10^{18}$ He/cm^2 requires SW simulation experiments that cannot be performed in the laboratory, because high beam intensity in excess of a few μA have to be used to reach a reasonably short long-duration implantation, which can be supported by both humans and the implanters ($\leq$ a few days). But then, space charges build up in the ion beam that got dispersed! Another nice alternative is that the target glows red upon heating and then melts! Therefore helium gets lost, never reaching the critical fluence.

From the best of our knowledge, for a flat target of silicate appropriately irradiated in an ion implanter, $\Phi_c(He) \sim 4 \times 10^{17}$ He/cm^2. This critical value will be reached in about 1,000 years of continuous exposure at 1 AU. But during the same exposure a micrometeorite flying in the interplanetary medium and a dust grain residing on the top surface of the lunar regolith would receive a fluence about 4 and 10 times smaller, respectively.

Let us consider a flat target of micrometeorite material of 1 cm^2 facing constantly the Sun for a duration, $\Delta \sim 200,000$ years at 1 AU. The flux and the He/p ratio of the solar wind are $\sim 4 \times 10^8$ p/cm^2 and 75/1900, respectively. This exposure time can be transformed into a fluence of SW-He incident on the flat target exposed in space, $\Phi_{ft}(He) \sim 10^{20}$ He/cm^2.

But this is not the fluence reaching all the surface elements of a 100 μm size rotating micrometeorite that faces the Sun half of the time, only during the "day". The flat target fluence has thus to be divided by two. Moreover, during the "day", the cross section of the micrometeorites, πR^2, perpendicular to the beam, intercepts a fraction of the incident fluence, $\Phi_{ft}(He) \times \pi R^2$. But this fraction hits the sunlit surface, $2\pi R^2$, facing the SW beam. Therefore, the fluence distributed on all the elements of surface of the micrometeorite is $\Phi_{ft}(He)/4 \sim 2.5 \times 10^{19}$ He/cm^2.

Now, with these basics, let us penetrate in the harsh interplanetary medium, where a freshly released micrometeorite ready for adventures has been injected without knowing that it will suffer terrible SW-sunburns during its flight time to the Earth which will end with a flash heating in the atmosphere, a freezing in Antarctica ice and a terminal crushing in the laboratory. What a nightmare!

The ~60 solar wind sunburns of the micrometeorite "skin". Translated in terms of the concentration of He in the top 50 nm of the test micrometeorite, and without knowing about the flaking of the He-loaded amorphous coating of a micrometeorite at a depth, R_p, the flux $\Phi_{ft}(He)/4 \approx 2.5 \times 10^{19}$ He/cm^2 implies that this layer was made of ~60 He atoms per target atom. It was thus transformed into solid helium just spiked with about 2% of micrometeorite material! What an odd solid except for a science fiction writer. I would have even shouted out with the help of my large megaphone, "IMPOSSIBLE"!

After about 4000 yr of exposure in space all the elements of surface of a micrometeorite reach the critical "sunburn" fluence, $\Phi_c(He) \approx 4 \times 10^{17}$ He/cm^2. A thickness of material, $R_p \sim 50$ nm, is removed, and a new fresh micrometeorite skin is generated that again starts the cycling to be implanted up to $\Phi_c(He)$, etc. When this complex recycling of solar wind implanted species has been repeated about 60 times over $\Delta \sim 200{,}000$ yr, the micrometeorite has received a total fluence of 2.5×10^{19} He/cm^2.

This severely limited the concentration of all SW species, including Ne, to a very small saturation concentration. It likely represents the last "spike" of SW-Ne with the longest projected ranges, i.e., larger than the mean value, R_p. They thus ended up being shielded below the boundary between the last heavily radiation-damaged surface that will flake off to space and the underlying still-crystalline substrate, right into the storage zone of SEP-Ne! Indeed, after ~60 peelings of the micrometeorite skin over $\Delta \sim 200{,}000$ yr, the initial external surface recessed inside to an approximate depth of 3 µm (i.e., 60×50 nm) in order to be right inside this zone, where SW-Ne lost its "personality" (i.e., its distinctive high 20/22 ratio). It would be released upon frictional heating simultaneously to SEP-Ne. Therefore, the 20/22 ratio can hardly be affected during the short pulse heating of micrometeorites upon atmospheric entry. Next let us demonstrate that SEP-Ne was not lost upon atmospheric entry!

The odd unit of "cc STP/g" shows no loss of SEP-Ne. This destructive high fluence regime was not reached during the implantation of the 10^5 times smaller fluence of the more energetic SEP-He, which were further injected well below the micrometeorite "skin". To compute this fluence, one needs to know the flux of SEP protons with energy of ≥1 MeV. For this purpose, one integrates the proton energy spectra, such as those reported by Goswami et al. (2001), from 10 MeV/amu (where the proton flux is about ~100p/cm^2/sec) to 1 MeV/amu, thus getting flux values about 50 to 100 times higher than at 10 MeV/amu. For a flat target, the flux of SEP-He is obtained by multiplying this value by the He/p ratio in the SEPs (about 2%). The fluence of SEP-He accumulated in T ~ 200,000 yr, is about $0.6{-}1.2 \times 10^{15}$ He/cm^2, which is far below the threshold of damage. The flux of SEP-Ne, $\Phi_{ft}(Ne) \sim 2.1{-}4.2 \times 10^{12}$ Ne/cm^2, is deduced multiplying the flux of SEP-p by the SEP Ne/p ratio as generally approximated by the value measured in the solar photosphere ($\sim 7 \times 10^{-5}$).

The mixture of neon trapped in AMMs is made of about 25% SW-Ne and 75% SEP-Ne. The value of its average concentration (1.5×10^{-5}cc STP/g) corresponds to about 4.5×10^{14} Ne atoms per gram of micrometeorite. Let us take a test spherical micrometeorite with a radius R, a density of 3 and a volume $V = 4\pi R^3/3$. The total number of SEP-Ne trapped in the micrometeorite mass is $0.75 \times (4.5 \times 10^{14}) \times V \times 3$. These neon ions have to penetrate throughout the external surface of a micrometeorite freely floating in space, and exposed to $\Phi_{ft}(Ne)$. Like in the case of the solar wind estimate, the effective fluence on all elements of surface of micrometeorites is about $\Phi_{ft}(Ne)/4$. We can thus write: $[\Phi_{ft}(Ne)/4] \times 4\pi R^2 = 3.4 \times 10^{14} \times (4\pi R^3/3) \times 3$ For a micrometeorite with a size of $\sim$100 µm ($R \approx 50$ µm) one finally gets $\Phi_{ft}(Ne) \sim 6.6 \times 10^{12}$Ne/cm^2.

This "experimental" fluence just deduced from the content of SEP-Ne in micrometeorites (i.e., totally ignoring the Δ value and the characteristics of the SEPs), is thus astonishingly similar to the value, $\Phi_{ft}(Ne) \sim 2.1–4.2 \times 10^{12}$ Ne/cm^2, deduced for a flat target flying in space for a duration $\Delta \sim 200,000$ yr. This fit shows that SEP-Ne locked in unmelted micrometeorites was not significantly lost upon atmospheric entry. As the 20/22 ratio is not expected to change upon atmospheric entry (because SW-Ne is trapped in the same retentive sites than SEP-Ne) this further implies that SW-Ne was not lost either!

There are two hidden uncertainties in this computation related to the long-term characteristics of the $\geq$1 MeV/amu SEPs, including its flux and its Ne/H ratios, as averaged on the long term and not over the last 10 years or so. Jean Duprat kindly evaluated the flux value used in this section from his "best" choice of energy spectra recorded for the contemporary SEPs over the last 10 years or so. The fit between predictions and observations for the SEP-Ne content of micrometeorites would thus yield the important information that the long term average of the product of the proton flux and the Ne/p ratio of the SEPs would have been rather similar within a factor 2 over about the last 200,000 yr. Let us turn to some experimental observations that comfort this SW sunburns history of AMMs.

Stepped pyrolysis of noble gases in AMMs. The *common sense* prediction that SW-Ne is preferentially lost upon frictional heating through a random walk would simultaneously imply a decrease in the bulk 20/22 ratio of micrometeorites. This is clearly not observed. For example, this ratio is independent of the residual Ne concentration in the individual AMMs analysis reported by Osawa et al. (2000, 2002).

Alfred Nier (1993) investigated $\sim$15 µm size SMMs. He states that "for the 10 cases where neon measurements could be made, the average value for ^{20}Ne/^{22}Ne was found to be 12 ± 0.5; for the three cases where ^{21}Ne/^{22}Ne could be made, an average value determined was 0.035 ± 0.006". These values are compatible with the corresponding ratios measured by Nakamura and Takaoka, (2000) in an aliquot of about 200 AMMs with sizes of 70–200 µm with the technique of total melting. As frictional heating sharply increases with increasing sizes, the 20/22 ratio should be clearly smaller in the largest size fraction.

Another information deduced from the data of Nier was obtained just by checking whether the content of SW-He (He is much more readily lost upon heating than Ne) correlates with the 20/22 ratio (the content of neon could not be reliably measured in these small SMMs). For the particles that yielded the highest and lowest 20/22 ratio (12 and 11.8, i.e., not much different anyways) the corresponding He contents are 27 and 170 –in the unit of 10^{-3} cc STP/g, respectively. This also invalidates the trend expected from frictional heating!

There is another counter evidence of a very different nature, which unexpectedly supports the SW-He sunburns scenario. The random walk required for a neon atom to reach the external surface in order to get lost, is much shorter for SW species than for SEP species. Consequently, *common sense* predicts that during stepped pyrolysis the SW and SEP components (as identified by their different 20/22 ratio) should be released at the lowest and highest temperatures, respectively.

The composition and the isotopic composition of neon were carefully monitored during the stepped pyrolysis of an aliquot of about 200 AMMs with sizes $\leq 70\,\mu$m (see Nakamura and Takaoka, 2000). The small amount of Ne first released at the lowest temperature of 400°C is not SW-Ne. This is the purest fraction of SEP-Ne with a 20/22 ratio of 11.3! Then SW-Ne is clearly released altogether with SEP-Ne in 3 distinct temperature steps between 700°C and 1300°C, where its relative abundance decreases from 40% to 15%.

This stepped pyrolysis shows that SW-Ne has been clearly redistributed in the trapping sites of SEP-Ne before atmospheric entry, as predicted by the SW sunburns scenario. *Thus, the value of the* $^{20}Ne/^{22}Ne$ *ratio has been fixed by the distribution of the flight times of micrometeorites in the interplanetary medium.* This caused us to attempt to use this ratio to trace back the variation of this distribution in the distant past (see Sect. 24.2).

Misleading inferences from the Moon. Colleagues also point out that lunar dust grains show the typical high 20/22 ratio of 13.8 observed in the SW. This would suggest that when dust grains are exposed in the interplanetary medium they dominantly accumulate SW-Ne. Therefore, as this ratio is much smaller in micrometeorites after atmospheric entry, a large fraction of the SW-Ne implanted in micrometeorites has been lost upon atmospheric entry.

But for reasons already outlined in the 4th Subsect. of this section this argument is wrong. The residence time of lunar dust grains on the top surface of the lunar regolith (5,000–10,000 yr) is just too short to allow the accumulation of a measurable amount of SEP-Ne in a huge background of SW-Neon about 500 times larger. Consequently, the 20/22 ratio of lunar dust grains has the SW value, just because the concentration of SEP-Ne is undetectable, unless relying on stepped chemical etchings to remove the shallowly implanted SW layer –in the low fluence regime effective on the Moon the SW-Ne has still not been redistributed in the SEP-Ne accumulation zone. Even after a strong frictional heating that would boil off 99% of its SW-Ne, a lunar dust grain would still show its initial SW ratio!

Summary. In brief, we end this unexpected visit to the nightmare SW-sunburns world of micrometeorites, to which a friendly reviewer kindly directed us, concluding that contrarily to all predictions of *common sense* the characteristics of neon measured in micrometeorites (at least their ^{20}Ne/^{22}Ne ratio) have not been significantly altered upon atmospheric entry. Therefore, neon also supports the micrometeoritic purity of the atmosphere.

Most of the good fits between predictions and the corresponding observations, which are piling up in this book, run against *common sense.* They are thus hard to believe even by myself! Critics are thus fast pointing out that we heavily rely on "circular reasoning" to disregard other models. A litterate reviewer further quoted that the EMMA hypothesis is presented pretentiously as a sort of *"Panacea Universalis"* capable of explaining almost every aspect of the early Earth; etc.

Before ending this section, I feel a strong urge to quote for the first time in this book the important thought of R.W. Emerson in 1841: *"A foolish consistency is the hobgoblin of little mind"*. It was already quoted by Owens (1992), who dared to be careful about the apparent consistency of his model concerning the formation of the Martian atmosphere!

The Ne-hobgoblin will be fully gone when we understand why the formation of the $\sim$1 μm thick magnetite shell of micrometeorites upon atmospheric entry did not simultaneously trigger some marked loss of neon. Did the shell decorate a very fast "radiation enhanced" recrystallisation of the top sunburned skin of the particles, which was loaded with stored energy due to radiation damage, and already strongly depleted in all types of noble gases? This shell might have quenched the loss of the more deeply seated neon. Now, I have to stop because I am starting to use my own *common sense*, which is as bad as that of the next guy.

19.4 Two "Relicts" of Early Micrometeoritic Neon in the Present-Day Atmosphere

The ^{21}Ne/^{22}Ne ratio of micrometeorites ($\sim$0.034) is very close to the atmospheric value of 0.029. Relative to this ratio, the atmosphere shows depletion in ^{21}Ne of about 10%, relative to the average micrometeoritic ratio. This depletion can be compared to the depletion of about 20% noted for ^{20}Ne, relatively to the average micrometeoritic ^{20}Ne/^{22}Ne ratio ($\sim$11.85) –and not to the much higher solar wind ratio of 13.8 considered in previous works.

The depletion of ^{20}Ne in the atmosphere looks thus two times higher than that noted for ^{21}Ne. This is expected from a single mass-dependent fractionation process effective in an early micrometeorite atmosphere, such as hydrodynamical escape –this process was already invoked to decrease the initial solar wind ratio previously predicted for the early atmosphere to the present-day atmospheric value. These correlated isotopic mass fractionations alone support the view that this process was effective on an early atmospheric neon very similar to that trapped in contemporary Antarctic micrometeorites, which inherited its recent composition from the distribution of the time of flights of micrometeorites in the contemporary interplanetary medium, during which they were irradiated by SW neon, SEP neon and SEP protons.

It would be a kind of "miracle" if these specific $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ ratios locked in AMMs were incorporated at much earlier times –i.e., during the making of the building material of the Earth in the early solar nebula through the astonishing variety of processes listed by Ozima and Podosek (2002)– and then subsequently degassed in the early atmosphere. Indeed, the distribution of the flight times of these much earlier dust particles in the solar nebula, at a time before the planets formed, was certainly very much different than today. Therefore, it looks more likely that micrometeoritic solar neon was delivered to the early atmosphere after the formation of the Moon (i.e., back to about 4.4 Gyr ago), at a time when the configuration of solar system bodies had more chance to be stabilized and rather similar to the present day configuration (c.f., Sect. 24.3).

19.5 A Relict of Micrometeoritic Neon in the Upper Mantle

As already outlined in Sect. 19.1, the solar neon rich MORBs (i.e., with a $^{20}Ne/^{22}Ne$ ratio ≥ 11.2) yield an average $^{20}Ne/^{22}Ne$ ratio of about 11.9, which fits astonishingly well the average micrometeoric value of about 11.8 (Maurette and Sarda, 2004). This strongly suggests that the unmelted fraction of the incoming micrometeorite flux deposited on the oceanic crust transfered its solar neon to the mantle. We had just to check that there was an ample supply of it, in order to balance the huge losses expected during the subduction of unmelted micrometeorites deposited on the oceanic crust. However, the $^{21}Ne/^{22}Ne$ ratio has not been preserved in MORBs. It shows a much larger excess of ^{21}Ne due to a nucleogenic ^{21}Ne component derived from U and Th decays (Ozima and Podosek, 2002).

We used the model developed for iridium with one difference: we consider that only unmelted micrometeorites (i.e., 25% of the incoming flux of micrometeorites) that get deposited on the oceanic crust can transfer a small fraction of their neon to the mantle. The quantity of solar neon carried by unmelted micrometeorites could not be reliably computed before, because the basic data and/or deductions required to develop the accretion formula were not available. They concern:

- the mass flux of the incoming micrometeorites;
- the composition of micrometeorites that has been invariant since the formation of the Moon (see Sect. 10.1);
- the proportion of micrometeorites that survive unmelted upon atmospheric entry of about 25% (Duprat et al., 2003);
- the physics of the giant Moon-forming impact that blew off the pre-lunar atmosphere and probably induced the last scavenging of iridium to the Earth's core (see Sect. 29.2).

With these data, the accretion formula yields the total amount of solar neon (1.5×10^{16} g) deposited on the oceanic crust by unmelted micrometeorites, mostly during the first 100 Myr that followed the formation of the Moon. A "bulk" Earth content of micrometeoritic neon can be derived by diluting it to the total volume of the whole mantle, which represents about 0.6 Earth's mass. This value is ∼300 times larger than the estimated neon content of rocks from the upper mantle. Therefore, there was an ample supply of micrometeoritic neon in the oceanic crust, in order to feed the very inefficient process required to only transfer about 0.3% of it to the upper mantle during subduction of the oceanic crust.

These observations of micrometeoritic neon in the upper mantle would support the delivery of the same micrometeoritic neon to the atmosphere by both the fraction (∼75%) of the incoming micrometeorite flux that is volatilized and/or melted upon atmospheric entry, and the delayed degassing of about 99% of the neon trapped in unmelted micrometeorites during the subduction of their host oceanic crust. We next illustrate how the simple observation of the micrometeoritic "purity" of the atmosphere, and the search for micrometeoritic "ashes" (i.e., Ir and Ne) in terrestrial materials, yield new hints about early Earth's processes.

20 The Micrometeoritic Purity of the Atmosphere and Early Earth's Processes

20.1 A Finely Tuned Occurrence of Early Earth's Processes

The basic time frame of EMMA is the formation time interval of the Earth, $\Delta(Earth) \sim 100\,\text{Myr}$. This value has been estimated from both the ^{129}I–^{129}Xe radioactive chronometer (Pepin and Phinney, 1975; Staudacher and Allègre 1982) and modern theories about the formation of the Earth initiated by Wetherill (1994) –for a recent summary see Canup and Agnor (2000). In this scenario, the composition of the Earth's atmosphere reported in Table 1 would give the average composition of about 1000 billions of billions of billions (e.g., $\sim 10^{30}$) of juvenile IDPs captured by the Earth after the formation of the Moon, and representing a total mass of material of $\sim 5.10^{24}$ g. Amazingly, this composition turns to be quite similar to that of an aliquot of about 500 AMMs with sizes of around 100–200 μm, amounting to a few milligrams of material, that we used to infer the composition of a "micrometeoritic" atmosphere.

When we realized in 1999 (Maurette et al., 2000) that the Earth's atmosphere was so "pure" we foresaw that six conditions had to be simultaneously finely tuned in time, relative to $\Delta(Earth)$ to produce such a stunning micrometeoric purity. They are:

- The timing of the Mars-sized Moon-forming impact, which had to happen near the end of $\Delta(Earth)$, in accordance with the recent predictions of Canup and Asphaug (2001). Otherwise, the micrometeoritic atmosphere would have been heavily contaminated by volatiles delivered by big bodies still to be accreted by the growing proto-Earth during the post-lunar period. In brief the Moon-forming impact was the last giant impact in the history of Earth accretion.
- The physics of this impact which had to blew off a major fraction of the previous atmosphere, thus preparing a kind of vacant niche for the growth of a new "post-lunar" atmosphere produced by the late arrival of comets in the inner solar system. This important problem is more adequately discussed in Sect. 29.2.
- The Hartmann conjuncture describes correctly the episode of the late heavy bombardment of the Earth–Moon system. In particular, this conjuncture

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suggests that a gigantic storm of micrometeorites was still effective after the Moon-forming impact over a period of about 100 Myr, in order to deliver the adequate quantity of volatile species in the atmosphere;
- Large impactors were still hitting the Earth in the post-lunar period. It could be argued that they possibly contributed to the formation of the Earth's atmosphere. However, they had to be made of a pure CM-type material, in order not to alter the chemical purity of the atmosphere. Furthermore their total mass influx was about 10 times smaller than that of micrometeorites (see Sects. 7 and 23);
- The degassing of the early mantle was quite fast, being mostly completed near the end of $\Delta(Earth)$. This deduction was first suggested by Sarda et al. (1985) from measurements of the isotopic composition of argon in both the upper mantle and the present day atmosphere. It allows minimizing another major contamination of the post-lunar micrometeoric atmosphere by the complex residual mixture of volatiles initially trapped in the building materials of the Earth (unless they were already quite "dry") during their formation in the early solar nebula.
- The composition of micrometeorites was basically invariant though time (Sects. 10.1 and 24.2).
- The recycling of the early atmosphere by plate tectonics and conventional volcanism, which releases a mixture of reprocessed gases quite different from the atmospheric mixture, was a marginal process –such a recycling is known to produce alterations of the initial gas mixture by processes such as the generation of an overwhelming amount of pyrolysates from alteration of organic matter and "serpentinisation".

If only one of these conditions is not verified –e.g, the corresponding parent event does not occur at the right time relative to $\Delta(Earth)$– it becomes impossible to account for the micrometeoric purity of the atmosphere. Therefore, this purity should help constrain the timing of these events, and consequently their nature. It can hardly be argued that the good predictions of EMMA just reflect a lucky –if not somewhat miraculous– chance coincidence. Indeed, the fit between predictions and the corresponding observations require the right tuning in time of these half a dozen very different events in the early history of the Earth.

20.2 The Right Cleaning Impact at the Right Time

We mostly rely here on the discussion presented in Sect. 3.2 involving two main stages of accretion in the formation of the Earth. During this period of growth of the young Earth that lasted about 100 Myr, one can expect the accumulation of a complex mixture of atmospheric components, which started when the Earth reached about 4 (Abe and Genda, 2002) lunar masses.

During a first and fast stage of "runaway accretion" lasting ≤1 Myr, the impacts of ∼10 km size bodies (probably mostly rocky) following orbits close to that of the future Earth fed its growth at relatively low impact speed (≤1.5 km/s). This fast process led to a "proto-Earth" of about 5–10 lunar masses, which already trapped a complex mixture of gases liberated during the impact of these rocky impactors, and/or captured from the solar nebula, which was not completely dissipated at this earlier stage. Simultaneously, about tens to hundreds of planetary embryos with masses of about 1 to 10 lunar masses were formed in all the volume of the inner solar system and the most massive ones, with masses ≥4 lunar masses, carried their own atmosphere.

The second stage of accretion lasted about 100 Myr. It mainly involved the impacts at much higher speeds of these massive embryos. Morbidelli et al. (2000) convincingly argued that the growth of an Earth-like planet involved typically half a dozen embryos. In about half of the 11 simulations reported in their paper one of these embryos originates from a zone beyond 2.6 AU, where hydrous–carbonaceous asteroids are confined today. Consequently, they could propose that this "wet" embryo with a size of about 1500 km could have been responsible for the formation of the Earth's atmosphere.

About 100 Myr after the isolation of the solar nebula the swarm of large planetary embryos became empty (Canup and Agnor, 2000), and the early solar nebula and its constituent volatiles was dissipated. The third stage of accretion took over. It involved a minor contribution of the impacts of asteroids, comets and leftover planetesimals forming a "late veneer" of small bodies. They contributed to the formation of the atmosphere either during their direct cataclysmic hits with the Earth, or through the accretion of the debris (including micrometeorites) that they released in the interplanetary medium during either collisions and/or the sublimation of the dirty ices of comets in the inner solar system.

If nothing severely hindered this complex accumulation of volatile species all along the formation time interval of the Earth, the contribution of these dust particles accreted by the Earth as micrometeorites would have been diluted in all these previous components. It is impossible to explain the micrometeoric purity of the atmosphere, unless the giant Mars-sized impact that formed the Moon simultaneously blew off most of the pre-lunar atmosphere and closed the formation time interval of the Earth.

However, in 1999, we got stuck with the age of the Moon. At this time dynamicists quoted arguments of celestial mechanics –considered irrefutable– to argue that the Moon could only be formed before the young Earth reached about 65% of its present-day mass (e.g., Canup and Asphaug 2001, for a review of previous works), that is well before the end of $\Delta(Earth) \sim 100$ Myr. Therefore, the micrometeoric purity of the atmosphere would have been blurred by the mixture of gases still to be delivered by the large impacting bodies that the Earth had still to "swallow" to grow to its final mass.

We were shyly asking an expert in this field whether the Moon could be older (on the nebular time scale) than previously thought. His answer was a stunning and impressive "IMPOSSIBLE" and we started seriously worrying about the validity of EMMA. Then, Canup and Asphaug presented in August 2001 their more accurate three dimensional modeling of the impact of a Mars-sized body with the Earth.

This was a great date in the life of young EMMA because their work made this "impossible" statement obsolete. It convincingly demonstrated that the Moon was formed when the Earth had reached about 99% of its final mass after the merging of the last planetary embryo. We could thus rely on earlier works (see Sect. 29.2) to deduce that this last giant impact also blew off the pre-impact complex atmosphere.

21 Extrapolation of EMMA to the Moon and Mars

In this section, EMMA is first extrapolated to the Moon, to hopefully get new clues about a confusing problem that people have failed to figure out since 1970. It deals with the so-called meteoritic contamination of the lunar crust in siderophile elements such as iridium, which was previously attributed to the crater-forming impactors and not to micrometeorites. We next move to Mars to try to check whether EMMA can account for the high sulfur and nickel contents of Martian soils measured with instruments carried by the rovers Spirit and Opportunity in 2004. Before 1999, this obscure contamination looked at first glance to be of a limited interest. Consequently, it was neglected in earlier works. We discovered recently that the true reason for this neglect was probably that the description of this contamination on the Moon and Mars requires facing an astonishing diversity of very difficult problems in planetology, in which we became bogged down. But it was too late to quit.

21.1 The Lunar Iridium Puzzle

From highland megaregoliths to thin mare regoliths. A major difference with the Earth is the lack of plate tectonics, which could have recycled the lunar crust, formed about 4.44 Gyr ago (Carlson and Lugmaier, 1988). Therefore, this ∼70 km-thick crust is still preserved in the highly cratered lunar highlands. They are made of a megaregolith with a thickness of about 20 km still under debate, composed of feldspathic rocks lighter than the underlying basalts of the lunar mantle on which they initially "floated".

It is generally believed that about 600 Myr after the formation of the Moon, a narrow "spike" of large impactors, presenting a maximum in intensity around 3.9 Gyr ago, and which lasted for about 150 Myr, struck the Moon. It formed the 12 prominent "post-nectarian" multi-rings impact basins (i.e. formed after the Nectaris basin back to ∼4 Gyr ago) with diameters ranging from about 300 km to ∼1300 km, which are observed on the near side of the Moon. Later on, these basins acted as depressions that were flooded by basaltic flows originating from magmatic chambers seated at depths of about 300–400 km in the lunar mantle and which are not related directly to the spike of impactors (Taylor, 1999). After solidification, these basalts were transformed into soils by repeated impact comminution at a

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time when the flux of impactors was considerably smaller. Therefore, they could only develop a thin regolith with an average thickness of about 5–10 m, which tops the mare (and also all the lunar surface).

Earlier views about the "meteoritic" contamination of the lunar crust and the "maturity" of lunar soils. Measurements of the Os/Ir and Ge/Ir ratio of "mature" (see below) lunar soil samples recovered from the thin mare regoliths showed that a material related to the CM-type chondrites has contaminated them (Wasson et al., 1975; Gounelle, 2000). Surprisingly, about 20 years after the pioneering work of Wasson et al., it was found that about about 95% of the AMMs are also related to the CMs (see Sect. 7.2). This opens the possibility that micrometeorites contributed dominantly to this CM-type contamination of the crust.

Let us first summarize the work of Levinson et al. (2001) aimed at assessing the total mass of "meteoritic" extra-lunar material, *M*, incident on the Moon since its formation, and thought to be delivered by the impactors that cratered the lunar surface. They first review previous works that help defining a parameter, ξ, which is *the mass fraction of the lunar crust that is of "meteoritic" origin.* These values, which range from about 2% to 0.3% going from the most "mature" to "immature" soils collected during the Apollo missions, were directly deduced from the concentrations of iridium measured by Wasson et al. (1975) in CM chondrites (~600 ppb) and lunar soil samples, which are summarized in Fig. 40. One can infer from this figure average values of the Ir contents of ~12 ppb and ~1.8 ppb for mature and immature soils, respectively.

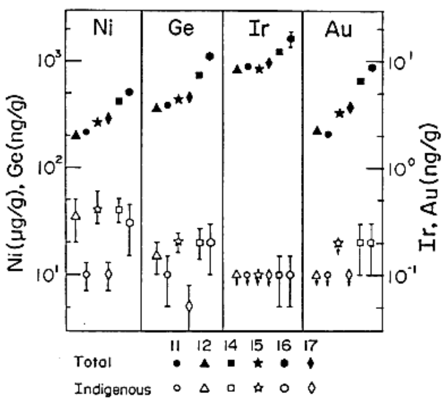

Fig. 40. Concentrations of Ni, Ge, Ir and Au measured in both mature lunar soils collected at the six lunar landing sites (closed symbols) and in the still mysterious "indigeneous" component found in the same soils (Courtesy of J. Wasson).

We recall that the "maturity" of a soil is related to the rate of recycling of its constituent dust grains on the top surface of their host regolith that is ruled by impact gardening (see Sect. 3.3), and which increases with time accordingly to the $K(t)$ curve (see Fig. 1). In this top position, they get exposed in particular to:

- solar wind and solar energetic particles, such as neon. Therefore the proportion of Ne-rich grains in a soil is a good index of maturity;
- melted glass splashes ejected upon impact melting, and which fall back on the soil producing "glassy agglutinates". Their proportion in a soil is also a good index of maturity that seems to rule the albedo of lunar soils;
- vapor phases deposits generated during the volatilization of large impactors and micrometeorites, which delivered iridium to the soils.

Levinson et al. next reviewed estimates of the thickness of the lunar crust where this *meteoritic* contamination was thoroughly mixed upon a deep gardening induced during the early intense impact cratering of the lunar crust. This depth of gardening is assimilated to the thickness of the megaregolith, which would be bracketed between about 35 km and 15 km. With a value of ξ varying from 2% to 0.3%, one ends up with estimates of the total mass of "*meteoritic*" material accreted by the lunar crust, M_A, which have ranged over two orders of magnitude, from about 5×10^{21} g to 8×10^{22} g and up to $\geq 5 \times 10^{23}$ g, depending on the choice of parameters made by Ryder (1999), Sleep et al. (1989) and Hartmann (1980), respectively.

The iridium contents used to infer the ξ values were delivered by the fraction, η, of the initial impactor mass, M retained after an impact, and which depends upon the impactor orbit. As pointed out by Levinson et al. this dependence represents *a more fundamental uncertainty.* This is well illustrated by the wide range of η values previously used, and which vary from $\ll 1$ to 0.5! With a reasonable value of $\eta \sim 0.1$, Levinson et al. deduce that the total *meteoritic* mass *incident* on the Moon, $M \sim M_A/\eta$, should now range from about 5×10^{22} g and 8×10^{23} g up to $\geq 5 \times 10^{24}$ g. As our objective was to predict the iridium contents of lunar soils, we had to develop a new "Ir-free" approach.

Micrometeoritic lunar "winds". At this stage, we defined a related "micrometeoritic" parameter, $\xi(MM)$, which is the *mass fraction of the lunar crust that is of "micrometeoritic" origin.* A great advantage of micrometeorites is that they allow deducing the value of this key parameter without relying on the concentration of iridium.

Like all other investigators, we had still to select the thickness of the lunar crust that was contaminated by the accretion of juvenile micrometeorites, i.e., the thickness of the megaregolith where an efficient impact gardening was effective. We selected a value of 20 km, within the range of estimates given by Levinson et al. (15–35 km), which was deduced from the propagation of

P-seismic waves, indicating a closure of porosity at that depth (Weismann, 1989).

Micrometeorites cannot be decelerated in the rarefied lunar atmosphere, and upon impact they are volatilized, together with a similar mass of regolith. The fraction of the incident flux of micrometeorites lost to space can be estimated with the "lunar wind" model developed by Langevin and collaborators (1975, 1978, 2004). Each of them thus forms a blob of very hot gas at about 10,000 K, which is defined as the lunar wind (LW). This wind expends very rapidly in the lunar atmosphere.

The following mass balance was established:

- less that 10% of the LW hits the neighboring grains, where it condenses as ultra-thin LW-coatings;
- 70% of the LW species have velocity in excess of the escape velocity ($\sim$2.36 km/s) and get lost to space;
- 20% of them do not reach the escape velocity. They thus stay in the rarefied lunar atmosphere for about three months. They interact with the solar wind, which deposits only 50% of the material on the lunar surface. After a second exposure to SW ions, 50% of this 50% get lost, etc. With this mass balance, only 20% of the incoming micrometeorite flux is deposited on lunar dust grains as LW-coatings.

The tricky gravitational focusing factor of the Earth. Computing the micrometeorite flux that struck the Moon since the formation of the lunar crust, at time, $t_1 \sim 4.44$ Gyr ago (Carlson and Lugmaier, 1988), from the corresponding Earth's value $\Phi(t_1) \sim 5.6 \times 10^{24}$ g, requires accounting for the larger gravity of the Earth which attracts more impactors and accelerate them to higher speeds than if they had struck the Moon. One has thus to multiply $\Phi(t_1)$ by the ratio, G, of the factors of "gravitational focusing" of the Moon and the Earth. These factors reflect the enhancement of their geometrical cross sections due to their gravitational attraction for approaching bodies, and they scale as

$$\pi R^2 \times [1 + (V_{\mathrm{esc}}/V_\infty)^2]$$

where R is the radius of the planet, V_{esc} the escape speed of about 11.2 km s^{-1} and 2.4 km s^{-1} for the Earth and the Moon, respectively, and V_∞ a critical velocity, which still poses a problem. It is considered as the approach orbital velocity of the impacting bodies at 1 AU prior to their gravitational acceleration by the Earth or the Moon. Then, the concept of LW indicates that about 20% of this mass flux will be retained by the Moon.

For the Moon, the low escape velocity of $\sim$2.4 km s^{-1} allows neglecting the gravitational enhancement, which reduces to the cross section of the Moon. But for the Earth gravitational enhancement become important below about 20 km s^{-1}. In particular, if one goes back in time in the early LHBomb, the solar system was still encumbered by planetesimals and debris. Some of them could have been still marauding around the orbit of the young Earth with very low approach velocities of 0.1 km s^{-1}. Then, gravitational enhancement would increases the geometrical cross section of the Earth by a factor of ∼10,000! One thus faces the problem of choosing the average speed of micrometeorites before their acceleration by the Earth during the LHBomb, and this is still an unexplored speed zone. One has thus to rely on the speed distributions observed today, which also poses problems!

The work of Grün et al. (1985) yields an average speed of micrometeorites in the interplanetary medium at 1 AU, before their acceleration by the Earth, of ∼20 km s^{-1}. These studies also show that about 99% of these micrometeorites have a cometary origin. Therefore, for cometary dust particles, the gravitational enhancement of the Earth can be neglected and G is about 1/13. The difficulty is that the gravitational enhancement of the flux of asteroidal particles after acceleration by the Earth is larger than in the interplanetary medium due to their lower approach speeds. The only available data which could yield the average speed of the mixture of asteroidal and cometary micrometeorites striking the Earth is the average speed of radar meteors that decorate the atmospheric entry of micrometeorites after their acceleration by the Earth. A value of about 30 km s^{-1} was inferred by Southworth and Sekanina (1973) from the observation of 20,000 radar meteors with masses of about 10^{-7}–0.1 g (this study was done in the framework of the *Harward Radio Meteor project*, which was founded by NASA in 1966).

However, this value reflects a highly biased distribution of speeds because the fastest meteors are preferentially seen. Southworth and Sekanina tried to correct this biased distribution as to get the real average speed of micrometeorites after acceleration by the Earth, $V_a \sim 14.5$ km s^{-1} –it can yield V_∞ through the relationship, $V_a = [(V_\infty)^2 + (V_{esc})^2]^{1/2}$. Unfortunately, this corrected value, which was lower that all other estimates, is still challenged today because it is based on a few simplifying assumptions that are still not fully understood (Taylor, 1995). Therefore, after getting tired to hunt for the right value, which is probably buried in one of many publications that we did miss, we took as an approximation for the average value of V_∞ for asteroidal micrometeorites the corresponding approach speed of 13 km s^{-1} quoted for Earth-crossing asteroids.

If this approximation is correct, G is bracketed between 1/13 and 1/23. Then, after taking into consideration the loss of about 80% of the lunar wind generated during the impact of micrometeorites, the total mass of micrometeorites that was retained in the lunar megaregolith, mostly during the first ∼100 Myr that followed the formation of the lunar crust, is about 4.8–8.6 × 10^{22} g. This value is quite comparable to the mass of the crater forming impactors retained by the lunar crust (∼8 × 10^{22} g), which was deduced by Sleep et al. (1989). Therefore, one cannot neglect the micrometeorite contribution. It is thus likely that the iridium content of the lunar soils yields just an upper limit of the contamination delivered by large impactors. In Chap. 7 and Sect. 23.4 (second Subsect.) we suggest that this contribution was about 5–10 times smaller than that of the micrometeorite flux.

A two-stage micrometeoritic contamination? One can expect this material to be well mixed during the impact gardening that created the megaregolith at the first place. The density of the megaregolith can be deduced from both the value quoted for its constituent feldspathic rocks ($\sim$2.7 g/cm^3) and the volume of pore space inferred from the propagation of the P-seismic waves, of about 50%. One thus ends up with a value of $\sim$1.5 g/cm^3. All these data yields a value of $\xi(MM) \approx$ 4.3–7.8 wt.%, which is about four times larger than the average value ($\sim$1.9 wt.%) reported by Wasson et al. (1975) from the measured average iridium content of mature lunar soils –this value is generally called the "generally agreed" reference value of the *meteoritic* contamination.

With this $\xi(MM)$ value, the iridium content of micrometeorites of about 620 ppb (Kurat et al., 1994) directly yield the Ir content of the megaregolith of $\sim$27–48 ppb, which is about three to four times higher than the value of about 12 ppb measured in mature soil. Therefore, EMMA predicts too much iridium. It might be that the large impactors scavenged a major fraction of this Ir to the lunar interior through the formation of pockets of melted rocks during large impacts (c.f., Sect. 3.4).

Could it be that scavenging was so much efficient that the iridium now trapped in the Mare soils was mostly delivered after the end of the LHBomb, since about 3.7 Gyr ago, right in the 5 m thick regolith of the Mare, which was simultaneously formed during this period? From the accretion formula (see Sect. 10.4), the integrated micrometeorites flux, $\Phi(t_2)$, which accumulated since (t_2), can be approximated by $\Phi(t_1) \times K(t_2)/K(t_1)$, where the value of $K(t_1)$ and $K(t_2)$ are directly red on the $K(t)$ curve at times (t_1) and (t_2), respectively. The value of $K(t_2)/K(t_1) \sim 5 \times 10^{-6}$, yields $\Phi(t_2) \sim 5 \times 10^{17}$ g. This amount of micrometeoritic LW-coatings, which was redistributed within the 5 m thick regolith, corresponds to a value of ξ $(MM) \sim 0.2\%$.

This value looks already 10 times smaller than the average value measured in the mature soils. Furthermore, solar wind sputtering greatly reduced it. Indeed, in this "post-spike" period, iridium was deposited on the grains at a rate about 100 times smaller than the solar wind sputtering rate. Consequently, these LW-coatings were just sputtered away and lost from the Moon, and the residual value of $\xi(MM)$ was much smaller than 0.2%.

This deduction is supported by an earlier search for LW-coatings on ilmenite grains (FeO, TiO_2) recovered from one of the most mature lunar soils (Dran et al., 1977). This search was conducted with the technique of Auger electron spectroscopy. It gave an upper limit of about 50 nm for the thickness of LW-coating made of a chondritic material on a 100 µm size grain. As this coating would contain about 620 ppb of Ir, it would correspond to a value of the Ir content *about 50 times smaller than the value observed in the mature* *soils!* In sharp contrast, during the first 100 Myr of the post lunar period, the deposition rate of the lunar wind in the megaregolith was 100 times larger than the SW sputtering rate. Therefore, LW-coatings did accumulate in the earlier megaregolith during the "pre-spike" period.

We end up with a model containing a major free parameter, which is the fraction of micrometeoritic iridium deposited in the lunar crust, which ended up being scavenged to the lunar interior during the LHBomb (it should be at least 50%). Furthermore, this model cannot explain (yet) the gap of the Ir contents by a factor of $\sim$100 observed between the mature soils and their minor "indigenous" component, which is strongly depleted in iridium. This mysterious component is assumed to be the initial material, which was comminuted to make the soils (i.e., probably mare basalts and "anorthositic" rocks from the lunar crust). Therefore, our detective lunar wind investigation on the Moon is (momentarily) stopped. We sense that a misfit between our prediction and the "generally agreed" iridium content of the mature soils of about a factor 3–4 is not devastatingly large (i.e., before considering the ad-hoc scavenging of iridium to the lunar interior). But the situation with the prediction of the micrometeorite contamination on Mars is even worse.

21.2 EMMA with Spirit and Opportunity on Mars

We consider nickel and sulfur that show high concentrations in the unweathered Concordia micrometeorites. These two important elements were also detected in Martian soils with the Alpha Particles X-Ray Spectrometer (APXS) on board the Martian rover Spirit that landed in January 2004. This robot is still functioning 11 months after landing, and has moved around over a distance larger than 11 km. Another Rover, Opportunity, has joined it. This rover also carries an APXS instrument to analyse the rocks and soils of Meridiani Planum, a far distant site at the antipodal position of the Gusev crater.

A lunar model for the formation of regoliths on the Martian crust. To investigate the effects of micrometeorite accretion on Mars one should rather start with the accretion formula developed for the Earth–Moon system, because it is well constrained by a variety of experimental data, including the composition of micrometeorites collected in Antarctica, and lunar cratering rates, which would reflect the variation of the amplification of the micrometeorite flux with time at the Earth's orbit. We recall that the formula developed for the Earth (see Sect. 10.4) depends on both $A(\%)$, which is the weight percent content of a given element, A, in juvenile micrometeorites (thought to be similar to the value measured in Antarctic micrometeorites), and $\Phi(t)$, the integrated micrometeorite flux since any time, t, after the merging of the last planetary embryo at time, t_1.

There are similarities and differences between Mars and the Moon, both envisioned as collectors of micrometeorites:

– Like on the Moon, there was no plate tectonics to recycle the early Martian crust. Therefore, highly cratered highlands as well as smooth plains that would correspond to the lunar mare are also observed on Mars. Astonishingly, the size distribution of the impact craters on Mars, the Moon and Mercury are strikingly similar, when they are displayed on the "R-plot" (see Fig. 41). In particular there is a large difference in the distribution noted for the highlands and the sparsely cratered smooth "mare" type formations (Weismann, 1989; Squyres et al., 1992);
– The lunar analogy would suggest a megaregolith thickness of about 10 km on Mars –this is the value which was inferred by Squires et al. from a gravitational scaling of the lunar value of about 20 km deduced from the propagation of P-type seismic waves (see previous section);
– One can also expect a thin lunar mare-type regolith with a thickness of about 5 m, formed since about 3.9 Gyr ago. It should top all the Martian surface, including the basaltic fills of depressions such as the smooth plains, which were possibly probably formed, as on the Moon, during the spike of impactors that invaded the inner solar system about 3.9 Gyr ago.

The situation on Mars is somewhat simplified for two reasons:

– there is no loss of micrometeoritic material through a lunar wind effect;
– most magmatic chambers, which outpoured basalts in depressions, originate from the Martian megaregolith (with the exception of much larger and younger volcanic structure such as Olympus Mons).Therefore, contrarily to the Moon, it can be expected that the flows of basalts did initially carry the same micrometeoritic contamination as their parent megaregolith. In this case, the S and Ni concentrations of Martian soils originating from the basaltic fills of the impact basins should be rather independent of the age of formation of the basalts, unless a large amount of liquid water was still running after this spike, to possibly wash out some zones of the 5 m thick regolith thus depositing salts such as sulfates on the Martian surface (Langevin et al., 2005).

A "two-shots" cartoon for the early evolution of Mars. To extrapolate EMMA to Mars we used a general cartoon of planetary evolution, which has been already outlined for the Earth in Sect. 3. In this cartoon, all terrestrial planets have the same formation time interval, $\Delta \approx 100$ Myr, which is closed at time t_1, corresponding to the mergin of the last and probably most massive planetary embryo. This last embryo produced other major effects. It blew off the pre-impact atmosphere and scavenged strongly siderophile elements to the planetary core.

It thus prepared a clean "niche" for the accumulation of micrometeoritic species including volatiles (see Chaps. 10 and 18), and siderophile elements (see Chap. 18). Another important actor in this cartoon was possibly the residual population of $\sim$500 km-sized impactors that could have boiled off the terrestrial oceans several times before about 4 Gyr ago (Sleep, 1989;

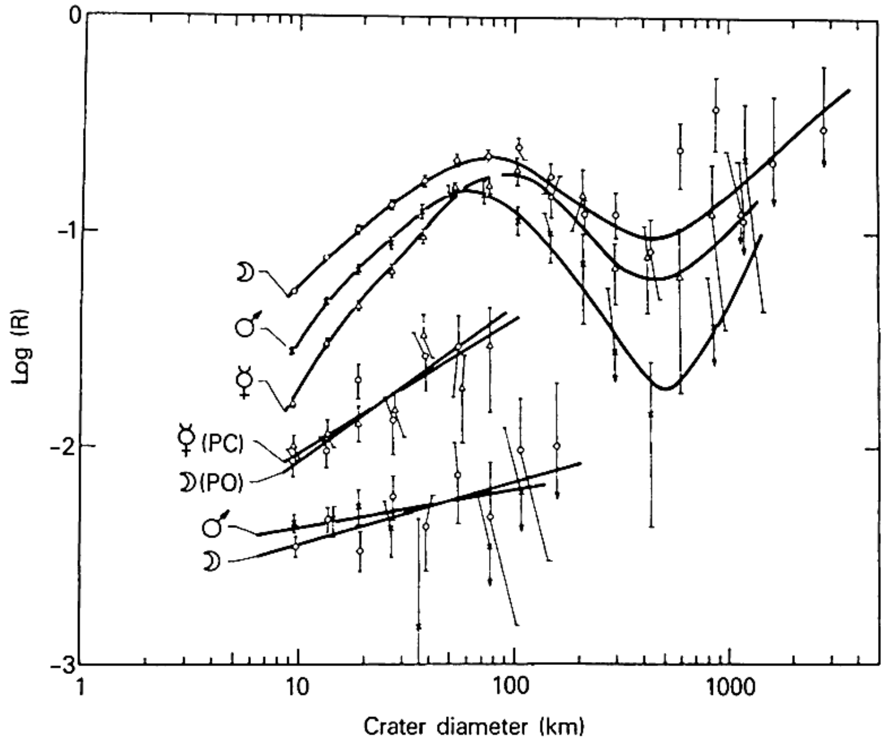

Fig. 41. Comparison of the *crater size/crater density* distribution of craters on the Moon, Mars and Mercury. The comparison will be limited to the three top curves and the bottom two curves. To enhance potential differences in the previous deceptive plots (they imply better statistics than are present) used to assess differences in crater size distributions, the *"Crater Analysis Working Group"* developed the "relative" size-frequency distribution plot, or *R-plot*, reported in this figure. The R-plot displays information about the differential size distribution of the craters –see Weismann (1989) for a concise three page explanation about this complex but most useful plot. The top three curves refer to the heavily cratered highlands on the Moon, Mars and Mercury. The two bottom curves refer to the sparsely crated areas on the Moon and Mars, which correspond to the lunar post-Mare and smooth young Martian plains, respectively (Courtesy of P. Weismann).

Zahnle and Sleep, 1997). Due to the lower gravity of Mars these impactors now had the potential to blow off the Martian atmosphere including salt deposits, thus resetting the niche for the accumulation of a younger and much thinner micrometeoritic atmosphere. A major adjustable parameter in this scenario is the date, t_2, of the impact of the last ∼500 km-sized impactor. We tentatively tried to constraint it from the total mass of CO_2, N_2 and Ne in the contemporary Martian atmosphere.

It should be noted that iridium is a “highly” siderophile element, which was fully scavenged on both the Moon (this is indicated by the very low Ir content of the indigenous component of the soils rocks) and the Earth (see Sect. 18). Furthermore, on the Earth, sulfur was also behaving as a highly siderophile element while being fully scavenged to the core (see Sect. 3.4). However, this does not necessarily apply to nickel, which is a “moderately” siderophile element that can be oxidized, and thus left behind in some minerals.

The tools of extrapolation to Mars. We assumed that the variation of the micrometeorite flux with the heliocentric distance corresponds to that measured for smaller approximately 10 µm size micrometeorites by micrometeorite detectors on board the Galileo spacecraft, and which roughly scales inversely to the heliocentric distance up to the orbit of Mars (see Fig. 42). There is a second correction, which gives the ratio of the diameter of the craters produced by an impactor with a given mass on Mars and the Moon, respectively. This factor should be used to correct the lunar cratering rates for the smaller orbital velocity of Mars, which reduces the kinetic energy liberated upon impact. As it varies by at most a factor of about 2 between the Earth and Mars, this correction was neglected.

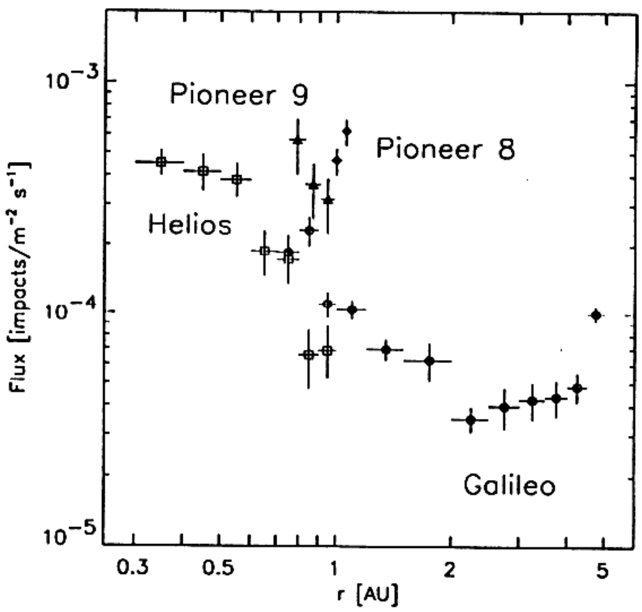

Fig. 42. Variation of the flux of interplanetary dust particles with the heliocentric distance measured with micrometeorite detectors on board several spacecrafts (Courtesy of H. Grün).

In these conditions, the value of the integrated micrometeorite flux delivered to Mars mostly during the first 100 Myr that followed the closure of its formation time interval by the last planetary embryo, at time t_1, can be directly inferred from the corresponding value estimated for the Earth, $\Phi(t_1) \sim 5.6 \times 10^{24}$ g. One relies on the ratio of the factors of gravitational focusing of the two planets, and the variation of the micrometeorite flux with the heliocentric distance. The integrated mass flux of micrometeorites since the end of the formation time interval of Mars is estimated to be about $\Phi(t_1) \sim 10^{24}$ g.

Accumulation of nickel and sulfur since the merging of the last planetary embryo. The sulfur and nickel contents of the Martian soils have been deduced from the X-ray spectra acquired by the APXS instruments carried by Spirit (Gellert et al., 2004) and Opportunity (Rieder et al., 2004). For the sake of illustration, we reported in Fig. 43 a part of the first bulk X-ray spectra (i.e., before data reduction) reported on the JPL Web site for the Gusev crater. If this spectra was induced either by X-rays or electrons like in conventional instruments, this peak would correspond to a high Ni content of about 0.3%. However, the proton beam used in the APXS instrument is about 10 times more efficient to produce the characteristic X-ray lines of elements heavier than iron. Now the Ni contents range from a lower value of 450 ppm for the soils of the Gusev crater to about 640–1090 ppm for soils of the Meridiani Planum. The sulfur contents show a narrower range of concentrations from about 1% to 3%.

The contents of S and Ni (about 5% and 1%, respectively) have also been recently measured in the new set of unweathered Antarctic micrometeorites collected in central Antarctica –see Sect. 16.1. The extrapolation of the accretion formula to Mars reveals that about 10^{22} g of Ni and five times more S were delivered to the Martian surface during the first 100 Myr that followed t_1. Assuming that micrometeoritic S and Ni were thoroughly homogenised in the 10 km-thick megaregolith, we end up with concentrations of Ni and S of about 0.2–0.7 wt.% and 1–3 wt.%, respectively – the lower and upper limits correspond to a density of the Martian soils which is bracketed between about 1 and 3 g/cm^3, respectively.

The sulfur content would well fit the values measured with the APXS instrument. This fit would suggest that this element was mostly deposited and redistributed into the megaregolith after the mergin of the last giant planetary embryo. Subsequently, it would have been recycled by a Martian volcanism rooted in magmatic chambers formed into the approximately 10 km-thick megaregolith. Consequently, it can be expected that the basaltic fills of depressions on Mars, which were quickly topped with a thin lunar mare type regolith, would show the same sulfur content inherited from their common parent megaregolith. This content would thus be independent of their formation ages with the condition that running water was not reprocessing the host sulfur compounds. But the predicted Ni content is about 3–10 times higher

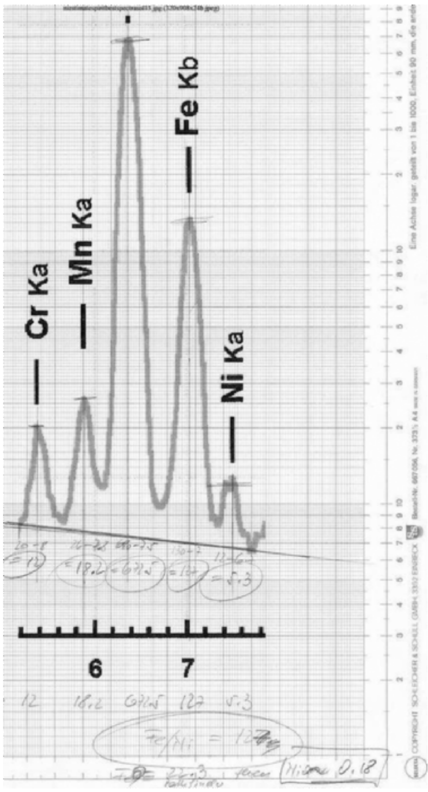

Fig. 43. First compressed X-Ray spectrum of the Martian soil obtained in January 2004 with the APXS instrument (*Alpha Particles X-ray Spectrometer*) on board the Martian rover spirit, which was available on the JPL Web site. It allowed a rough estimate of the Ni content of the soil, which has to be subsequently decreased to take into consideration a contamination of the Ni signal by a component of the instrument –the extend of this contamination was a confidential information that was not released on the JPL WEP site.

than the observed values of about 450–1090 ppm. What are the implications of this misfit?

A double impact history for neon, nitrogen, CO_2 and Ni? Let us consider the ad-hoc occurrence of the late impact of a 500 km body at time t_2, which could have blew off the first micrometeoritic atmosphere and scavenged nickel at time t_2. By assuming that Ne, N_2 and CO_2 in the Martian atmosphere were delivered as on the Earth by juvenile micrometeorites since this second and last major impact, the best measured partial pressure of CO_2 on Mars ($\sim$7.5 mbar) yields the amplification factor, $K(t_2) \sim 800$ from which a value of $t_2 \sim 4.15$ Gyr is inferred. This amplification yields the total mass influx of micrometeoritic nickel of about 4×10^{18} g, which was deposited on

Mars since $t_2 \sim 4.15$ Gyr, as well as the right amounts of Ne, N_2 in the last thin Martian atmosphere!

The next conjuncture is that this amount of nickel was redistributed by impact gardening within a thin lunar mare type regolith formed on top of the Martian megaregolith. A difficult problem is to fix its average thickness. Another potential problem is running water, impacts and dust storms that might have remobilized Ni. With a thickness of ∼5 m, similar to that observed on lunar Mare the bulk Ni content of this regolith, of about 3600 ppm, is about 4 times higher than the range of values measured with the APXS instruments on board of "Spirit" and "Opportunity". But a regolith formed since t_2 (i.e., at a time of higher impact rates) should be thicker than 5 m. This would decrease the misfit between predictions and observations.

21.3 A Hard Time for EMMA on the Moon and Mars

This *double impact* scenario inferred from the Ni and S content of Martian soils and the partial pressure of CO_2 in the contemporary atmosphere faces two major difficulties. First, it is generally believed about the frequency of the 500 km size impactors on the Earth that "there is a fair likelihood that there was none between 3.8 and 4.1 Gyr ago" (see Zahnle and Sleep, 1997). This fair likelihood should be even more probable with the smaller cross section of Mars.

The high sulfur content of the Martian soils corresponds well to the prediction of EMMA concerning the accumulation of the micrometeorite contamination in the Martian megaregolith since the impact of the last planetary embryo occurring at about the same time as on the Earth. But the amount of Ni simultaneously delivered vanished. A possible interpretation is that a late 500 km size impactor, which simultaneously blew off the first micrometeoritic atmosphere, scavenged Ni. In this case, why is it that sulfur was not behaving as a highly siderophile element (i.e., like on the Earth) as to be scavenged together with Ni at the same time?

The second difficulty is even worse. The high sulfur content would imply that about 20 to 50% of the Martian soil would be made of a CM-type chondritic material. This major component of the soil should give a clear imprint of a chondritic composition in the APXS spectra of the Martian soils. This is not observed, as this spectrum contains in particular too much Al, Ca and Ti.

In brief, we have not solved, yet, the stumbling blocks of the unavoidable micrometeorite contamination of the Lunar and Martian crusts. We got stuck in a conjuncture of difficult problems, rooted in:

– Modern scenarios of the formation of the terrestrial planets, that predict that the formation time interval of the terrestrial planet was closed by the merging of the last planetary embryo;

– The modelling of the period of the late heavy bombardment;
– The formation and preservation of a “megaregolith” on the heavily cratered highlands of the Moon and Mars;
– The existence of 500 km-size bodies still marauding in the inner solar system until $t_2 \sim 4.1$ Gyr ago;
– Lunar and Martian volcanisms that filled up depressions, in order to form sparsely cratered lunar mare and Martian smooth “plains” topped with a thin regolith;
– the fate of water on Mars, which possibly washed out this thin regolith.

Using micrometeorites to probe early planetary processes only gives us a sense of parts of the early obscure history of the terrestrial planets and of the only large Moon in the inner solar system. However, like on the Earth, we might be unexpectedly on the right track of the origin of the Martian atmosphere, as EMMA would predict rather well the partial pressure of CO_2 and the Ne/N_2 and CO_2/N_2 ratios measured today in the Martian atmosphere.

This scenario has the potential to account for the large amount of running water predicted by Fanale (1999) during the early history of Mars –equivalent to a approximately 300 m thick global layer. Indeed, during the time interval between the merging of the last giant planetary embryo and the strike of the last ∼500 km-size impactor, EMMA predicts that an amount of micrometeoritic water equivalent to a approximately 700 m thick layer was delivered to Mars. It also gives a series of exercises in planetology that hopefully might help us to become more familiar with the Moon and Mars. This is like with tourism. If you are just a tourist in vacation you cannot understand the country. But as soon as you are working in the country, even for a short while, then it might be much easier to understand it. New questions were formulated while comparing the predictions of EMMA to the corresponding measurements and we might be on the right track with the origin of the Martian atmosphere. This is again suggestive of an intricate conjunction between giant impacts and the accretion of microscopic juvenile micrometeorites in the formation of the atmospheres of the terrestrial planets. However, we have to find additional “witnesses” of the early Martian history in order to avoid being trapped like other colleagues with models loaded with free adjustable parameters.

Part VII

Parent Bodies of Micrometeorites and Early Solar System Processes

So far we have wandered in the post-lunar area while being protected by solid data that helped constrain speculations, such as the composition of the Earth's atmosphere, the contents of S and Ir in rocks from the primitive upper mantle, iridium in lunar samples, and Ni, S and CO_2 concentrations measured on Mars. We were outside the boundary where science sometimes merges with science fiction. In this part we reach this dangerous boundary several times while moving to the pre-lunar area dealing with the obscure first $\sim$100 *Myr history of the Earth. Here, good data become rare and bold speculations overabundant. To guide us, we have only the most primitive meteorites and micrometeorites used as probes of early processes, observations of young Sun-like stars and computations of planetary dynamicists. However, camping on these boundaries is an exciting part of the scientific adventure, loaded with the "unexpected". In these sections we question the nature and the provenance of the parent bodies of micrometeorites, which is still hotly debated. We next venture into the still obscure early history of comets, which begin in a cradle of dust and ices. In their early stage of formation, these ices were probably dusted by huge surges of dusty solar gases. The trip will (momentarily) stop at the dead end of the early configuration of solar system bodies and nearby stars, which is one of the most eluding but fascinating mysteries of our distant past.*

22 The "Hunt" for Micrometeorites Parent Bodies

The application of the accretion formula to the Earth–Moon system does not require the identification of the parent bodies of micrometeorites (i.e., asteroids or comets). However, this identification is necessary to better extrapolate this formula to other terrestrial planets, such as Mars. One would also like to understand how the invariant composition of micrometeorites constrains the nature of their parent bodies. We report on a few arguments that have not been thoroughly explored yet, and which run against the conventional view that most micrometeorites originate from the collisions and/or erosion of asteroids. The only remaining alternative is that they dominantly originate from comets.

22.1 Conventional Views: a Small Abundance of Cometary Micrometeorites

Before atmospheric entry. The Infrared Astronomy Satellite observed dust bands (IRAS-band) associated with families of main belt asteroids, as well as dust trails delineating the orbits of comets, in the zodiacal cloud –this cloud in which micrometeorites are temporarily stored, fed the flux of the dominant "sporadic" micrometeorites accreted by the Earth. This shows that the micrometeorite complex includes dust particles originating from both interasteroidal collisions (mostly occurring between about 1.8 and 4 AU) and the sublimation of the dirty ices of comets, which is mostly ignited at a heliocentric distance smaller than about 2.5 AU.

There is already some discordance about the measurements of the relative abundance of cometary dust particles in the micrometeorite flux, *Comet (%)*, made with Earth-orbiting spacecrafts. Micrometeorite impact measurements from Earth's orbit show that the cometary contribution is higher than 75 % of the total dust influx rate for the whole Earth (Zook, 2001). This is compatible with the view that in the large size range, the abundance of asteroidal particles sharply decreases with increasing size. Indeed, large particles are affected more by their lifetime against mutual collisions, τ_{COL}, than by their longer lifetime, τ_{PR}, against the radiative drag of the Poynting–Robertson effect, which induces their spiraling to the Sun (Burns et al., 1979). Moreover, they are also more frequently temporarily trapped in mean motion resonances of

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the planets (MMRs) defined in Sect. 1 (Liou and Zook, 1997). However, a numerical modeling of IRAS data concludes that *Comet (%)* is smaller than 25% before atmospheric entry (Dermott et al., 2001).

A temporary storage in the Earth "resonant" ring. The lifetimes, τ_{PR} and τ_{COL}, are not related to the terminology defined from radioactive decay (such as half-life, period and mean life), and defined for a population of bodies that somewhat exponentially declines with time (see Sects. 3.1 and 2.3). For example, the lifetime of a particle injected on a circular orbit in the asteroidal belt that spirals to the Sun is given by its average flight time to the Sun. For a small particle with a size, $s \sim 10\,\mu\text{m}$, this is just the value computed for only the PR drag that scales as $a^2 s/Q$, where a is the orbit radius and Q a poorly known factor ranging from 0.1 to 1. But for a large particle with a size, $s \geq 100\,\mu\text{m}$, which is also subjected to a gravitational force that scales as s^3, this flight time now includes not only the PR drag, but also the temporary storage time in MMRs around a planet.

Indeed, the orbit of large particles evolved more slowly under the PR drag. Therefore, they spend more time around an MMR, and this increases their probability to be captured in it. Density enhancement of interplanetary dust particles by this effect has been found in the so-called Earth "resonant" ring, which was first inferred from the modeling of the IRAS data and subsequently confirmed by in-situ measurements performed on the "Cosmic Background Explorer" spacecraft.

Colleagues are confused when they hear about this ring of "asteroidal" particles around the Earth, concluding that this "belt" feeds dominantly the micrometeorite flux captured by the Earth with asteroidal material. But most particles trapped in this ring quickly escape the resonance (i.e., in a few thousand years) and start migrating outward to the next MMR around Venus, before finally escaping it and flying directly to the Sun –see Grün et al. (1995), their Fig. 22. The relatively high inclination of the orbits of most visible and radar meteors show that they cannot originate from a kind of discharge of particles from the Earth resonant ring onto the Earth, because these ring particles would be mostly confined to the ecliptic plane.

Furthermore, numerous periodic comets have perihelion near orbital resonances of Jupiter located in the asteroidal belt (e.g., both mean motion and secular types). The dust particles that get dispersed along their orbit can be trapped in these resonances, lose energy, get circularized, and look like an asteroidal particles while leaving the belt. They will also be trapped in the Earth ring as true asteroidal particles. We could thus argue that the proportion of cometary dust particles is quite high in the Earth "asteroidal" resonant ring anyway!

After atmospheric entry. Moreover, atmospheric entry would sharply decrease *Comet (%)* because the higher speeds of cometary dust particles would both decrease their gravitational enhancement near the Earth due to their high approaching velocities (i.e., their gravitational focusing) and enhance their destructive frictional heating upon atmospheric entry. All types of simulations of atmospheric entry as yet reported (including "pulse" heating with furnaces and numerical and/or close form mathematical calculations) would indicate that in the large size range (≥100 µm) of AMMs, *Comet (%)* would be reduced to a few % –see Brownlee (2001) for a review of some of these works.

22.2 The Inadequacy of Previous Simulations of Atmospheric Entry

The disturbing high proportion of large unmelted micrometeorites. However, these "corrected" proportions are not reliable. This was shown by Philippe Bonny (1990), who developed the most elaborate computer simulation proposed as yet –his work was fully published in French in a 110 page report (Bonny, 1990a) and in a 226 page PhD (Bonny, 1990b), but only very briefly summarized in English in *LPSC* at a time when the computations were not fully completed (Bonny et al., 1989). The only trustworthy prediction that could be directly confronted by a straightforward measurement in these earlier times is the ratio of unmelted to melted (i.e., cosmic spherules) micrometeorites, P_{um}, measured in the collections of large micrometeorites with sizes ≥100 µm recovered on the Earth's surface. He concluded that none of the simulations (i.e., including his own) could account for the high value of P_{um} of about 25%, which was already measured in November 1984 in our first collection of Greenland micrometeorites.

Let us focus on the most favorable choice of the low average speed (∼15 km/sec) of micrometeorites deduced from the high average speed (∼30 km/sec) of radar meteors (see Sect. 21.1, 3rd Subsect.) that increases this proportion. Predictions of this proportion grew steadily from about 1% in 1985, when it was measured in the first collections of deep-sea spherules (c.f., Fig. 5 and Sect. 5.2) to ≤10% today. But the misfit got even worse about one year ago, when Duprat and Engrand measured a proportion of about one in their new Concordia collection (Duprat et al., 2003). Furthermore, the misfit sharply increases with the speed of micrometeorites, and this ratio drops to about one percent for a speed of about 27 km/sec. Consequently, micrometeorites are much better preserved upon atmospheric entry than previously thought, and reliable predictions of the final value of *Comet (%)* after atmospheric entry are not reliable yet.

Revelations in a supersonic air flow about the good thermal shielding of large micrometeorites. The pioneering work of Ballageas (1974) with a supersonic air flow, the modelling of Bonny and the experimental measurements of Jenniskens and collaborators (see Sect. 16.4) gives a few hints to understand why these simulations are inadequate. The computations might be possibly valid in the case of a perfectly smooth sphere made of a single crystal of anhydrous silicate. But they cannot describe the fate of a kind of cosmic sponge with a fluffy structure, loaded with volatiles, and made of very small grains that protrude on the external surface. The new feature considered by Bonny is that their internal structure mimics the thermal shields used to protect the space shuttle and missiles during atmospheric entry.

The components of micrometeorites with a low thermal stability, such as the carbonaceous material and hydrous silicates (saponite starts dehydrating at 100°C) are discomposed by endothermic reactions at low temperatures. This cools down the material from the inside. Moreover, the resulting gases percolate throughout the leading edge and collide with air molecules. This forms a compressed gas gasket much larger than the surface of the leading edge, which might contribute to further deflect air molecules before they hit the leading edge, and thus limit heating. A high temperature wake (at ∼10,000 K) develops in front of the particles, and the resulting cascades of collisions propagate behind the particles as to form a lower temperature wake at 4000 K. Additional processes are also switched on. For example, the porosity of micrometeorites first increases (i.e., before they reach the melting stage), and the micro-pores get loaded with the cold gases percolating from inside. This increases the thermal insulation of the porous layer, and delays the inward propagation of the heat wave, etc.

Even with his much improved modelling, Bonny could only decrease the maximum temperature evolved upon atmospheric entry by a mere 100°C, which was insufficient to increase P_{um} beyond 10%. In fact, the pulse heating of a tiny cosmic missile involves processes that are still poorly understood. One could even convince peoples that the "Queen Elizabeth" steamer could have survived intact upon atmospheric entry, while playing rightly with all the parameters of the "available parameter space" attached to the steamer, which is now anchored in a secret cove waiting to be dismantled.

The only valid simulation of atmospheric entry can only be done in a real supersonic airflow and not in the surprising variety of furnaces used by our colleagues. One of this valid simulation was described (in French) in an internal report of Balageas (1974) and then briefly discussed (again in French) by Bonny (1988). It was conducted on the material considered in the numerical simulations of Bonny, which was composed of a mixture of 70% of silica fibbers and 30% of phenolic resin. Balageas monitored in particular the weight loss of the carbonaceous component of this composite material, which was investigated previously as a potential thermal shield of missiles. Using heat rates varying from 5°C s^{-1} to a maximum value of 100°C s^{-1}, he observed the typical phenomena of "delayed" pyrolysis of this material. When the heat rate is 5°C s^{-1} about 50% of the carbonaceous component is lost at a temperature, $T_c \sim 570$°C. But when the heat rate is 100°C sec^{-1}, T_c shifts to 1100°C. The rather regular spacing between the 4 loss curves observed at rates of 5°C, 20°C, 50°C and 100°C per second, allows deducing that for a fast cometary micrometeorite suffering a heat rate of 500°C s^{-1}, T_c

would be shifted to about 1500°C! It looks like the proportion of micrometeorites heated up at a temperature, T_c, inferred from the available models of atmospheric entry has no meaning, because T_c refers to ordinary laboratory temperatures. In fact, during atmospheric entry low heat rates looks more damaging than high heat rates! Therefore, the prediction that cometary particles are preferentially destroyed (i.e., relatively to slow asteroidal particles) upon atmospheric can hardly be trusted.

Several observations illustrate the good shielding of AMMs during atmospheric entry. In particular the studies of solar neon trapped in a random mixture of ~100 µm size AMMs (collected by our Japanese colleagues in the sediments of the water tank of their Dome Fuji station) indicate an average content of neon in the particles of about 1.6×10^{-5} cc STP/g. In Sect. 19.3 devoted to the severe SW-He sunburns history of micrometeorites, we showed that this value is very close to that expected from the implantation of SEP neon during the flight time of AMMs in the interplanetary medium. But neon artificially implanted into silicate targets starts to be lost at "laboratory" temperature of ~600°C. With this low release temperature conventional models would yield a proportion of Ne-rich micrometeorites, which did not get heated up above 600°C upon atmospheric entry ,smaller than 0.1%.

22.3 Additional Evidence for a Cometary Origin of Micrometeorites

The short ^{21}Ne and ^{10}B exposure ages of Antarctic micrometeorites. ^{21}Ne and ^{10}Be are "cosmogenic" nuclides produced during the nuclear interactions of energetic protons with the constituent atoms of micrometeorites, which accumulate during their so-called cosmic ray exposure age. Micrometeoritic neon has a unique ^{21}Ne/^{22}Ne ratio relative to that found in HCCs and lunar mare soils (see Sect. 19.2 and Fig. 34). Its average value of about 0.034 reflects a very small excess of cosmogenic ^{21}Ne in micrometeorites relative to the primordial ratio of about 0.029 observed in the Earth's atmosphere –this is not due to a loss of ^{21}Ne upon atmospheric entry (see Sect. 19.3). In sharp contrast this excess is much larger in both HCCs (i.e., CI-, CM- and CR-type chondrites) and lunar soils directly scooped from the 5 m thick regolith on the lunar mare.

On the Moon, these large excesses represent a typical pure effect of the reprocessing of material within an approximately 5 m thick lunar mare type regolith, where they can be exposed to protons from both the SEPs and the galactic cosmic rays (GCRs), when they reside at depths of a few cm and of a few meters, respectively, which load them simultaneously with ^{21}Ne. The constituent grains of meteorites that are breccias, such as the gas-rich CI-and CM-type chondrites, were also recycled within the regolith of their parent asteroid before being compacted into a single breccia to become gas-rich grains. These breccias were ejected into the asteroidal belt, where they spent

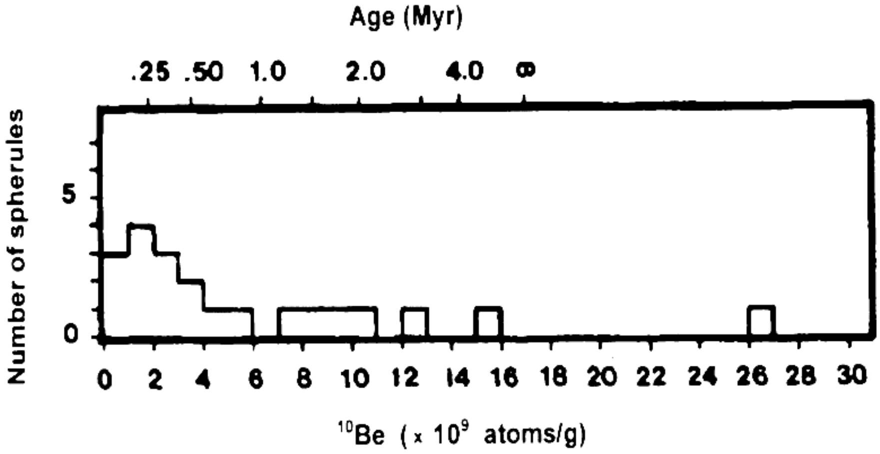

Fig. 44. Distribution of the ^{10}Be exposure ages of Antarctica micrometeorites and large cosmic spherules from both Greenland and Antarctica (Courtesy of G. Raisbeck).

most of their remaining cosmic ray exposure age, until they were trapped in mean motion resonance with Jupiter, from which they could be more easily dislodged and fired to the inner solar system.

When the neon isotopic composition of their minor component of solar gas-rich grains (about 10% of the grains) is reported on the three isotopes plots it looks very similar to that of lunar dust grains. In sharp contrast, the strong depletion of ^{21}Ne in AMMs would reflect that their parent bodies were denuded of a regolith.

This would exclude an asteroidal origin, because remote sensing studies show that all observable stony asteroids are capped with regoliths (see last rubric in Sect. 3.4). The only plausible alternative is that their parent bodies are periodic comets, probably originating from the Edgeworth–Kuiper belt, which lost their very heavily irradiated top "crust" and/or cometary regolith after a few returns to the inner solar system (Osawa et al., 2000). This small content of ^{21}Ne in AMMs is also compatible with the wide distribution of their low exposure ages in the galactic cosmic rays, deduced from another cosmogenic isotope, ^{10}Be (Fig. 44), which peaks around 200,000 years. Raisbeck and Yiou (1986, 1987, 1989) observed this distribution in melted and unmelted micrometeorites recovered from Greenland and Antarctica. They already used it about 25 years ago to argue that large AMMs have a cometary origin, because this value is clearly smaller than the value of a few Myr expected for the spiraling to the Sun of an approximately 100 µm size grain ejected during interasteroidal collisions in the main belt and subjected to the Poynting–Roberston drag.

The image of comet Borelli appears to show an appreciable regolith, and it was argued that many periodic comets are not denuded of a regolith. In fact, some cometary crust might have become thick enough to be coated by a kind of regolith, which is gardened during the passage of the comet at perihelion, when gases propel "geysers" of dust that partially fall back on the cometary nuclei as a "grain rain". However, if the ablation of a comet is about 1 m during each passage at perihelion, the lifetimes of the dust grains in such cometary regoliths would not be long enough to allow the particles to acquire high ^{21}Ne content. Therefore, micrometeorites ejected from cometary regoliths would still show a depletion of this isotope relative to the excess observed in a gas-rich asteroidal regolith breccia.

The invariant composition of micrometeorites. Most data about the zodiacal cloud used in this section were found in Bailey et al. (1994), and in a concise chapter written by anonymous authors in a "book" available on the JPL Web site (see Ref. TPF, 2004). One of the arguments in favor of an asteroidal origin of most micrometeorites today is that the debris of interasteroidal collisions can easily feed the zodiacal cloud. In particular, a collision of two approximately 10 km sized bodies is expected in the contemporary main belt about every 10^7 years, and only one of these collisions will completely replenish the present-day mass of the zodiacal cloud ($\sim 2.5 \times 10^{19}$ g).

In Sect. 10.1 we argued that the composition of interplanetary dust was invariant with time over about the last 4.4 Gyr. The implications of this invariance in term of the nature of the parent bodies of micrometeorites are still poorly understood. However, it is unlikely that such an invariant dust composition could have been extracted from the asteroidal belt, which contains a variety of bodies. The major reason is that if the micrometeorite flux is produced during the collision of two asteroids, they generate a dust input in the zodiacal cloud that lasts for about 10^6 years. Therefore, as the rate of collisions between large asteroids ($\sim$10 km) is about one very 10^7 years, only the most recent single collision yielded the micrometeorites collected today. Their composition could hardly be similar to the composition of the ancient micrometeorite flux as imprinted in the composition of the atmosphere, which would represent the average of many interasteroidal collisions during the first 100 Myr of the post-lunar period!

On the other hand, the giant belt conveyor system that was likely operating in the early solar nebula (c.f. Sect. 24.1) could have peppered distant cometary ices with a well homogenised dust component formed in the inner solar system, and carrying refractory phases such as anhydrous crystalline silicates observed in the dusty tail of the Hale–Bopp comet. In this case, these dust grains were formed at about the same time, at the same place (i.e., the inner solar system). Therefore, their composition would be invariant with time even thought the compositions and the provenance of their host cometary ices may vary (Mumma, 2002).

The high friability of the new Concordia micrometeorites. Figure 27 illustrates the very delicate structure of one of the new highly friable S-rich micrometeorites with sizes of 100 μm, recovered from the Concordia collection, and which represent about 50% of the fine-grained unmelted micrometeorites.

Some of them are so friable that they just crush into fragments when they are delicately touched with a needle. Such particles could have hardly survived through the rather rough reprocessing of particles in a parent asteroidal regolith, involving multiple depositions and ejections through ejecta blankets generated upon impacts and that felt back as a grain rain. Indeed they are not present in meteoritic breccias. This comment should also apply to the fluffiest particles discovered in the SMM collection (see Sect. 26.1). Again, we are stuck with the only alternative that these friable particles are cometary dust grains. They could thus be lifted off softly from their parent cometary ices. A few 100,000 years later they landed softly in fresh porous Antarctica snow.

At Concordia they were recovered through a gentle gravitational siphoning of melted snow water on a nylon sieve from which they were handpicked with the soft nylon hairs of a tiny brush (this technique might be even less destructive than that used for the stratospheric collections, which involves the impact of the dust carrying air flow with the dust collector at a speed of ∼200 m/sec). They look rather similar to the normal fraction of the ordinary fine-grained AMMs already observed in all our previous collections, with the exception of their friability and their easily weathered components such as sulfides and carbonates, which were leached out in the Cap-Prudhomme collection. Therefore it is likely that the bulk flux of micrometeorites originates from comets.

It was suggested that the particle reported in Fig. 27 looks similar to the constituent material of the odd Tagish Lake carbonaceous chondrites. This might suggest that the parent body of this odd meteorite is also related to the population of the parent bodies of at least contemporary micrometeorites. However, these friable grains constitute only a minor component of Tagish Lake. Moreover, the much higher D/H ratio of this meteorite indicates that it is made of a different material (see last subsect. in Sect. 24.1).

Not enough mass in the asteroidal belt? We already started this discussion in Chap. 7 (see 3rd Subsect.). The present day mass of the asteroidal belt, $M_{ast} \sim 3 \times 10^{24}$ g, represents about 4% of the lunar mass, or about 50% of the total mass influx of micrometeorites $\Phi(t_1) \sim 5 \times 10^{24}$ g. Asteroids on normal non-chaotic orbits in the belt are very stable against collisions. For example, the lifetime of a 10 km size asteroid against collision is ≥2 Gyr. Furthermore, even though the small asteroids “die”, those larger than 100 km (they represent about 90% of M_{ast}) just self repair by the re-accretion of the debris into “rubble piles”.

Consequently, asteroids are nor easily lost from the belt, and it is currently though that the mass of the initial asteroidal belt was at most 10 times larger than today, i.e., about $5\Phi(t_1)$ –see the work of Gomes et al. (2005) that comforts earlier estimates of Arnold (1964). About 90% of this mass was ejected in all directions after fragmentation. But the Earth looks like a tiny dot when it is viewed from 3 AU and it could only intercept a minuscule fraction of this asteroidal mass ejected in the interplanetary medium. Furthermore, it is unlikely that the total mass of the ejected asteroids was fully comminuted into a fine-grained dust. Therefore, asteroids cannot be the parent bodies of early micrometeorites.

A very efficient sand blasting machine in the interplanetary medium. Until recently, the "generally agreed" dust content of cometary nuclei, of about 20%, turned to well correspond to both the visible observations of the coma of comets in the visible and in-situ measurements made during the visits of the Giotto and Vega spacecrafts to comet Halley, in 1986. But recent observations challenge this value (Lisse et al., 2005). It is quite clear that much more dust is observed in the coma of comets during observations in the near and far IR than in the visible. In fact, observations of comet P/Encke and P/IRAS with IR telescopes on the ISO and MSX spacecrafts show dust-to-gas mass loss ratio about ∼50 times larger than those inferred from measurement in the visible! These high loss ratios were recently reconfirmed for comet Temple 1 during the Deep Impact mission.

They just sense the top layer of the comet, which is certainly much more enriched in dust than the bulk cometary nuclei. This layer thus acts as both a remarkable magazine of dust projectiles, and as a powerful sand blasting machine to fire them to space with the assistance of jets of gases formed during the sublimation of cometary ices and propelling the dust at speeds of about 200 m/s. This remarkable feature might just reflect the formation of a cometary crust by the dust that fall back on the comet as a "grain rain" (see Sect. 3.4, last Subsect.). But A'Hearn et al. (2005) observed on comet Temple 1 "several dozen apparently circular features, ranging from 40 to 400 m". They note that the size distribution of these features is consistent with that of impact craters. This indicates the existence of a regolith type reprocessing of the ices during impact, which also enriched the dust component up to depths of about 100 m, at least around the major impact sites.

This surface enrichment should not noticeably affect the dust content of the core of the comets, which is probably ∼20 wt.%. However, Lisse et al. outline that it would considerably enhance the proportion of cometary dust in the zodiacal cloud, where micrometeorites are temporarily stored for about 200,000 yr, before striking the Earth. Before this work, the low dust production rates of comets quoted and the rate of apparition of fresh comets in the inner solar system (about 1 per year) led to the conclusion that comets could hardly provide more than 10% of the zodiacal cloud mass. Now, their much enhanced dust production rate suggests that they can provide the bulk of the zodiacal dust. This supports the much earlier work of Grün et al. (1985), who did use micrometeorite detectors on board of spacecrafts to deduce about 20 years ago that 99% of the interplanetary dust grains in the zodiacal cloud originate from comets.

22.4 Search for Leonid Cometary Micrometeorites from the Cold

The proponents of an asteroidal origin of micrometeorites will probably challenges all arguments presented in favour of a cometary origin. This problem might be solved if the Stardust spacecraft returns safely (on January 15, 2006) a few large dust particles collected in the tail of comet Wild 2, on the condition that they have not been markedly altered during their very sharp deceleration in the aerogel collecting surface that they striked at speeds of ∼6 km/sec (c.f., last subsect. in part IX). Nevertheless, since January 2000, Duprat et al. (2001)have been preparing a crucial test of our claim, facing the hard challenge of recovering a few tons of snow from specific annual snow layers deposited in both Greenland and Antarctica at the time of intense historical Leonid meteor showers (Fig. 45).

These showers, such as those of 1833 and 1966, are produced when the Earth intersects the dusty orbit of comet Temple–Tuttle. These annual snow samples should have captured 100 μm sized "Leonids" with a well-certified cometary origin. If AMMs that mostly originate from the sporadic flux of micrometeorites are indeed cometary dust particles, the model of dust transport by huge surges of solar gases discussed in Sect. 24.1 would predict that the composition of cometary dust is independent of their host comets even though the composition of cometary ices clearly varies from one comet to the next.

AMMs recovered in Antarctica as yet originate from the sporadic flux of micrometeorites, which leave radar and visual trails showing a quasi-random distribution of their inclinations. In contrast, Leonid shower particles have parallel trajectories because they follow the comet orbit. They thus produce short trails that seem to radiate from a single spot (radiant) in the constellation of Leo.

If we are right, AMMs should be strikingly similar to the Leonids with two noticeable exceptions. Similarities include their mineralogical, chemical and isotopic compositions. The two exceptions are both related to their much shorter flight times in the interplanetary medium of a few centuries at most (Jenniskens, 2001) –and not of a few 100,000 years for the dominant micrometeorites of the sporadic flux, which are not associated with meteor showers. Therefore, they should show a pure component of solar wind neon with no measurable contamination of SEP neon (Cuillierier et al., 2002), and their carbonaceous component would have been much less degraded into a kerogen by SEPs ionization effects (c.f., Sect. 14.1).

Fig. 45. An approximately 5 m deep trench was excavated quickly near the Concordia station (left). It started to be exploited in January 2002 to learn about how to recover samples from the horizontal annual snow layer of 1966. This layer, which should be buried at depths of 4–4.5 meters, might contain micrometeorites and spherules delivered by the November 1966 Leonid meteor storm with a well certified cometary origin (Courtesy of J. Duprat).

These two exceptions should help identify such Leonids, in the expected case where they turnout to be similar to the dominant background of micrometeorites from the sporadic flux. Establishing this similarity between the two families of shower and sporadic micrometeorites would support the cometary origin of most Antarctic micrometeorites. Moreover, it would also validate various implications of this origin, such as the occurrence of a huge mass transport process in the early solar nebula that peppered cometary ices with dust particles made in the inner solar system.

The predictions of the models of atmospheric entry briefly discussed in Sect. 22.2 have convinced most people that the very high speed ($\sim$ 70 km/sec) of micrometeorites from the Leonid showers destroyed them, while increasing their frictional heating upon entry. Heating certainly increases with size. This is reflected by the proportion of melted micrometeorites that increases from 20% to 50% when the size of the particles increases from about 50 µm up to 200 µm, and by the marked loss of their solar wind helium that increases with their sizes. However, these models are already inadequate. They were already used back in 1982 to reject our first proposal to collect unmelted micrometeorites in Antarctica, as they predicted that the ratio of unmelted AMMs to cosmic spherules was about 1% for the favorable average speed of micrometeorites deduced from radar trails, a value which turned to be about 100 times smaller than the observed value at Concordia! Their extrapolation to the high-speed regime of shower micrometeorites cannot be trusted.

Recently, Jenniskens and collaborators measured with a new instrument the thermal structure of meteor wakes produced by large micrometeorites with sizes of about 1 mm to 1 cm, called minimeteorites (see Sect. 16.4). They are induced by collisions between ablation gases released by the particles and air molecules. This thermal structure shows very little dependence on both the initial mass and speed of the incoming particles. It could thus be argued that the hottest skin in front of the particles would be at a similar temperature for either an asteroidal particle or a fast cometary particle originating from the Oort cloud, and this would reduce the effect of the increased speed of the Leonids. Therefore, there is some hope of finding Leonid particles in the 1966 snow layers at Concordia in spite of predictions of inadequate classical models.

23 No Consensus About the Early History of the Lunar Impact Flux

A French word, "errance" (the straightforward approximate English translation is wandering) well describes the functioning of the mind when you do not know where you are going. You feel dumb just knowing that you will probably end up somewhere else. Then, you bury this shameful weakness of your neuronal system in the deepest secrecy and start again hunting for good data. However, this is an essential step of scientific inquiry, which is illustrated here below just wandering about the meaning of lunar cratering rates and the origin of comets, which are intimately interwoven with the early history of the solar system and in particular with the phenomenon of debris disk around stars.

23.1 The LHBomb in the Debris-Disk Sun

It is likely that the clearing of the disk of residual planetesimals (i.e., asteroids and comets) around the planets was triggering the LHBomb, which was partially recorded in the inner solar system by both the lunar crust (formed back to 4.44 Gyr ago), and the Earth. Greaves (2005) pointed out that until a recent time, since the work of Habin et al. (2001), astronomers reported that 15% or more stars belong to a new class coined as the "*debris disk*" stars, where dust is continuously regenerated by collisions of planetesimals (probably comets). In the case of a Sun like star, this disk was formed after the dissipation of the first parent dusty nebular disk observed during the T-Tauri evolutionary stage of a young Sun like star, which lasts for about 10 Myr.

The disks were first found to be rare around stars older than a few hundred Myr. But it was subsequently found was this phenomenon is much more frequent and that it might last for much of the lifetime of some stars on the main sequence. Unfortunately, the modeling of both the very different shapes and decay time of these disks have only been tentatively made in the case of very spectacular disks observed around Vega-type stars that are just asleep along the main sequence since about 4 Gyr, and such as ε Eridani at about 10 light-years from the Earth (Dent et al., 2000). The Sun also belongs to this class of stars, but it could not manage to retain for more than 500 Myr such a spectacular disk.

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Clearly, with lifetimes varying from 10–20 Myr (for transition stars that have still not reached the main sequence) to 100–10,000 Myr for main sequence stars, it is tempting to endorse the following deduction of Greaves: "The debris phase might be analogous to Earth's early period with a high-impact rate called the heavy bombardment". This episode of late heavy bombardment would be a quite ordinary by-product of the debris disk phenomenon, where the planets either accrete or scatter away the planetesimals of the disk. They have to migrate because of the resulting exchange of angular momentum with the planetesimals (Tsiganis et al., 2005). Thus the clearing of the planetary zones resulted in planetesimals both of a rocky and icy nature being flung throughout the solar system.

The $K(t)$ curve giving the variation of lunar cratering rates with time relative to the current value, would be a unique fossil record that monitors the jolts of a young star trying to reach the main sequence while dragging a residual mass of material of about 0.015 solar mass around it. A minute amount of this mass gave birth to the planets and to a debris disk that yielded the late veneer of dust accreted by the Earth after the formation of the Moon, and which represents about 3×10^{-9} solar mass. Fortunately, scientists have still very divergent views about the shape of $K(t)$, and this opens the way for new adventures in the mysteries of our distant past.

In 1975, George Wetherill (1975) already outlined 4 plausible processes that could have triggered the LHBomb, which shaped $K(t)$. Then, in 1981, he gave one of the best critical discussions of the questionable interpretation of the distribution of the formation ages of lunar breccias as directly yielding the shape of a late spike of impactors. He was also very carefully about pointing out major difficulties with each ones of these scenarios, and selecting meaningful data to better constraint them. This attitude of mind is generally lost today at a time when the scientists and their institutions worry too much about attracting the attention of the so-called "prestigious" journals, which only attract the attention of the major new agencies and consequently of the media. They do so with the "virtual" worlds created by the computer, which are indestructibly chained to their obscure and dangerous *"available parameter space"*, where a large number of adjustable free parameters, corresponding in particular to unproven initial conditions, are frequently hiding.

The list of these processes included in particular the exponential decay of the swarm of residual rocky planetesimals (asteroids) in the inner solar system that cross the orbits of Venus, the Earth and Mars, and a late formation of Uranus and Neptune related to the lower density of material in their formation zone, and which destabilized the EdK-belt. He also suggested that mean motion "resonances" in the orbits of giant planets (see Sect. 23.3) in the outer solar system might have also destabilized the EdK-belt. In these two last cases, the ejected comets should have generated kind of late "spikes" of impactors, coined later on as cataclysmic.

Then, about 15 years later, Hartmann et al. (2000) presented an extensive discussion about the history of the lunar impact flux. The 4 co-authors of this paper had conflicting views about what they call in their Fig. 3 "the empirical history of the lunar cratering flux", i.e., $K(t)$. The major conclusion of this courageous effort is summarized brilliantly as follow: *Because of several uncertainties and controversies about the conditions of the first few hundreds millions years, this review leads more toward continuing research problem than final solutions.*

Therefore, when we started this work at about the same time, we did not hesitate to continue the research problem about $K(t)$ without any hope to avoid controversies. Besides classical constraints that we initially considered as strong, we selected a few new constraints extracted from the fossil record imprinted in the Earth-Moon system.

23.2 The Fossil Record

The old record of the Earth-Moon archives. The late heavy bombardment was partially recorded in the inner solar system by the lunar crust (formed back to 4.44 Gyr ago) but also by the Earth. Due to the lack of water weathering and plate tectonics most of the lunar record is still preserved. It consists of both:

- Impact craters with diameters $\geq$4 km that were used to plot reliably the $K(t)$ curve up to about 3.9 Gyr ago. This curve had them to be extrapolated beyond this date with models, which generate a surprising variety of curves;
- The distribution of the formation ages of lunar breccias and lunar meteorites that would support the existence of a late spike of impactors between 3.8–3.9 Gyr ago;
- The 45 major multi-ring impact basins with size of $\geq$300 km formed since the occurrence of the South Pole-Aitken basin with a size of $\sim$2600 km, and which includes the 12 youngest basins observed on the near side of the Moon. It is generally considered that they were formed after the Nectaris basin, i.e., less than about 4 Gyr ago, but before their flooding by basalts, which formed the oldest mare back to 3.7–3.8 Gyr ago. About 8 of them are observed as single basins with sizes $\geq$800 km, and they somewhat cluster around the lunar equator. They include Imbrium, Nectaris and Serenitatis. They were considered as milestones supporting the existence of the late spike of impactors;
- The so-called "meteoritic" contamination of the lunar crust inferred from the iridium contents of lunar samples, i.e., the total mass, M_A, of extraterrestrial material that was retained in the lunar crust, and which was previously attributed to the crater forming impactors (see Sect. 21.1);
- the thickness of the megaregolith on the heavily craterized lunar highland, $\Delta_{lh} \sim 20$ km, which is potentially a good integrator of the flux of large

impactors that can excavate fresh material from the bed rock below the megaregolith.

Most of the earlier record has been erased from our active blue planets, where the oceanic plates are recycled about every 200 Myr on the average –i.e., between the opening of the plates and the formation of mountain ranges that close this cycle. Some useful components of this record include:

- The atmosphere and the upper mantle of the Earth. In particular, the total amounts of neon and nitrogen measured in the atmosphere when coupled to the concentrations of these two elements in micrometeorites directly yield an average value of the integrated flux of micrometeorites during the post-lunar period, $\Phi(t_1)$, without knowing about either the nature of the parent bodies of micrometeorites or the early history of the lunar impact flux (see Sect. 10.3). A third independent and rather similar value can be inferred from the iridium content of rocks from the upper mantle and the average Ir content of micrometeorites;
- Iridium and Os in deep sea sediments;
- The invariance of the CM-type composition of the "meteoritic" material accreted by the Earth (see Sect. 24.2). Since the formation of the lunar crust, this composition has been decrypted from very different sets of data, such as the chemical and isotopic compositions of the volatiles trapped in both the Earth's atmosphere, micrometeorites from Antarctica and fossil micrometeorites trapped in the achondrite Kapoeta back to ∼4.2 Gyr ago;
- Well preserved old detrital zircons found inside pebbles from one of the most ancient Australian cratons. They revealed the existence of an oceanic crust on a cool Earth as early as 4.3–4.4 Gyr ago. During plate tectonics, some extensive zones made of granite are lighter than the oceanic crust. They thus "float" on it, slowly derive, but do not participate to mountain building. They are thus still preserved in the oldest "quiet" zones observed in Australia, South Africa and Canada, coined as cratons.

Decrypting the last 100 Myr impact record with dinosaurs, deep sea sediments, and atomic and TNT bombs testing. Impactors with masses larger than 1 g are too rare to be investigated on a time window of one year with an impact detector of 1 m^2 orbiting the Earth, or with their radar and visible meteors in the atmosphere. Indeed, a detector of 10 km^2 would be hit by one impactor of ∼1 g and $\sim 10^7$ micrometeorites with a mass of $10^{-4} - 10^{-5}$ g during this one year exposure. For a flux of cometary particles for which the gravitational enhancement of the cross section of the Earth is negligible, the lunar flux per unit of time and unit of surface (usually 10^6 km^2) would be similar (see Sect. 21.1).

In the case of large impactors that are very rare the whole Earth's surface is used as a detector. We already described the hunt for Ir and Os in deep sea sediments that integrate the contributions of micrometeorites, comets and asteroids (Chap. 7). Scientists also try to decrypt the record of historical explosive events over the last 100 Myr, hunting for their fossil imprints, which include famous examples such as:

- The $\sim$2200 km^2 of devastated forest and the strong seismic signal produced by the Tunguska event in 1908;
- The impact that accelerated the extinction of the dinosaurs around 65 Myr ago, spiked a worldwide layer of sediments with iridium, and formed the $\sim$200 km-size Chicxulub crater in the Yucatan peninsula. This crater is invisible to the naked eyes, because it is buried under a km-thick layer of sediments. It was discovered by the perseverance of a bunch of scientists during a three dimensional mapping of local gravity and magnetic field variations that clearly showed its multi-ring structure.

One can relate this record to the explosive power, E, of the impactor (i.e., its kinetics energy), while relying on explosion craters formed during atomic and TNT bombs testing. They reveal that the volume of the crater is related to E. More precisely, the diameter of the explosion crater, D_c, scales as $E^{1/\beta}$, where the value of β ranges from 3 to 4 (with a "generally preferred" value of 3.4). Furthermore, this scaling can be extrapolated to the Moon because it is not very sensitive to the acceleration of gravity (it scales as $g^{1/5}$). An interesting simplification is that comets and asteroids with the same sizes have about the same explosive power, because their difference in density (a factor 3) is compensated by the higher speed of comets (about 13 km s^{-1} and 24 km s^{-1} for the average approach speeds of asteroids and comets, respectively, before their acceleration by the Earth (see Sect. 21, 4$^{\text{th}}$ Subsect.). The corresponding impact speeds are about 17 km s^{-1} and 27 km s^{-1}, respectively.

The date of these events and their reconstructed explosive power, E, yield a curve that gives the frequency of the impactors as a function of E, which only covers the last 100 Myr of our impact history. This energy is generally expressed in megatons equivalent of TNT, where $1MT = 4.2 \times 10^{15}$ Joules. On this scale, the explosive power of a typical asteroid will be about 100 times higher than the explosive power of a similar mass of TNT. Grieve (1998) reported a beautiful illustration of this method relying on 5 known fossil explosive events (see his Fig. 13).

This method does not differentiate between comets and asteroids, but it separates clearly their mass contribution from that of micrometeorites. One gets about one explosion of 10^8 MT per 100 Myr. This corresponds to the impact of a $\sim$10 km size asteroid and/or comet every 100 Myr, which yields a mass influx for the whole Earth of about 16,000 and 6,300 tons per year for asteroids and comets respectively. If comets were the dominant impactors on the Earth-Moon system, this mass influx represents about 15% of the micrometeorite contribution. This value would be a kind of upper limit for the series of estimates of about 3%, 4% and 10%, which were previously inferred in Sect. 7. Therefore, we considered that the contemporary mass influx of comets, ϕ_0, as averaged over the last 100 Myr, would be approximately

$\phi_0 \sim 0.1 \times \varphi_0$, where φ_0 is the current mass influx of micrometeorites of ~40,000 tons per year.

Connecting the present and past impact records. The basic assumption of EMMA is that the variation of the micrometeorite flux with times, relatively to the present day value, φ_0, scales to that of crater forming impactors, illustrated by the $K(t)$ curve reported in Fig. 1. Therefore, the total micrometeorite mass influx, $\Phi(t_1)$, since the formation of the lunar crust at time, t_1, is given by the product of the integral of $K(t)$ by φ_0. An approximate expression of this integral is $K(t_1) \times \tau$, where the value of $K(t_1)$ of about 2×10^6 is directly red on Fig. 1, and $\tau = 1.44 \times t_{1/2}$, is the mean life of the swarm of impactors responsible for the steeper decline of $K(t)$ during the first few 100 Myr of the post-lunar period, when the impactors have approximate half-life, $t_{1/2} \sim 50$ Myr –this value was first suggested by Wetherill (1975).

But $K(t)$ is the function first designed for describing the time evolution of the swarm of crater forming impactors. Therefore, the total mass influx of large impactors since t_1, $\Psi(t_1)$, is given by the product of the same integral by the contemporary mass influx, ϕ_0, of the impactors. In this case, the ratio $\Psi(t_1)/\Phi(t_1)$ just scales as the ratio of the corresponding present day mass influx, $\phi_0/\varphi_0 \sim 0.1$, even though the variation of $K(t)$ with time includes burst of spikes, bumps, etc. The value of $\Psi(t_1)/\Phi(t_1)$ would then be independent of the very complex solar system history imprinted in $K(t)$ at the conditions that comets always represented the dominant impactors that struck the Earth.

23.3 Conflicting Conjunctures

Early misfit between EMMA and the cataclysmic spike. In the late 1999, when we made this basic assumption, there were two distinct conjunctures proposed to explain $K(t)$. They included the "*accretion tail*" of Hartmann (i.e., a roughly exponentially decaying impact rate) and the "*terminal lunar cataclysm*", which was produced ~600 Myr after the formation of the Earth and the Moon by a narrow spike of impactors (from now on this scenario will be just coined as the *spike* scenario). Tera et al. (1974) first inferred this spike conjuncture from their measurements of the ages of lunar breccias (see next section, 4$^{\text{th}}$ Subsect.). Later on, Ryder (1990), Levinson et al. (2001) and Gomes et al. (2005) further developed this conjuncture.

As indicated in Sect. 10.4, the integration of the curve proposed by Hartmann predicts a value of $\Phi(t_1) \sim 5.6 \times 10^{24}$ g. This value well agrees with the direct neon and nitrogen estimates obtained without worrying about the early history of the impact flux. On the other hand, the approximate integration of the early version of the spike of impactors gave a value of $\Phi(t_1)$ about 200 times smaller than the neon and nitrogen estimates. So we neglected the contribution of this spike, even though we were quite impressed, as all new comers in the field, by the apparent clustering of the ages of the largest giant lunar impact basins visible on the near-side of the Moon, around 3.8–3.9 Gyr ago. The Hartmann's curve, which thus did look validated, was previously interpreted by Wetherill.

The residual swarm of rocky planetesimals. In his classical interpretation, Wetherill (1975), considered the swarm of residual planetesimals (asteroids) with orbits intersecting those of the Earth and Venus and their temporary perturbations to mars-crossing orbits. The initial number of bodies in this swarm would decrease rapidly with a $t_{1/2}$ value of 17 Myr during the first 100 Myr of the post-lunar period. During the next several 100 Myr (i.e., until about 4 Gyr ago) the number of earth-crossers decreases more slowly with $t_{1/2}$ values ranging from 50 to 200. This increase in half-lives is a consequence of impactors being stored in Mars-crossing orbits and the difficulty of re-establishing earth-crossing. With this interpretation, $K(t)$, looks like a radioactive decays curve (see Fig. 1) involving 3 distinct species, which would decay with half-lives of 17 Myr, 50–200 Myr and $\geq$900 Myr, during the first 100 Myr of the post-lunar period, the first few hundreds Myr of this period and after the end of the LHBomb around 3.5 Gyr ago, respectively.

But, we slowly piled up evidences supporting the deduction that the parent bodies of micrometeorites were dominantly comets (see Sects. 7 and 22). In this case the majority of the lunar impactors that craterized the Moon were comets. Some unknown processes should have fired them to the inner solar system, where they had to be subsequently trapped into Venus-, Earth- and Mars-crossing orbits, as to decay like the asteroids considered by Wetherill. How could it be that their average cratering rate relative to the present day value so well mimics that initially predicted for a swarm of rocky planetesesimals? This hardly be a chance occurrence when so many parameters are involved in the making of $K(t)$.

Wetherill has a unique blend of talents. He was initially a good experimentalist trained to measure the age of rocks, and he thus knew about their tricky "model" ages, including those of lunar breccias. This greatly helped him to select the best data around to constraint his models. Moreover, he never forgot to quote other alternatives when he was supporting a specific process. He thus commented: "*if comets where formed originally in the vicinity of Neptune and Uranus, and then transferred to the Ort cloud by planetesimals, planetary and stellar perturbations, the flux of comets into the inner solar system and the rate at which they impact planets during the first several hundreds million years is likely to have been* 10^4 *times the rate at present*". This argument is not outdated. Accordingly to Gomes et al. (2005), Uranus and Neptune were formed in the Jupiter-Saturn zone at the first place. But there was already a primordial disk of comets located around the current orbits of the two planets, in which they ended up roaming after a resonant crossing of the orbit of Jupiter and Saturn.

Stunning late bursts of migrations in the outer solar system. Gomes et al. (2005) reported the most complete dynamic simulation of the formation of the cataclysmic late spike of impactors on the Moon. This spike would result from bursts of migration of the giant planets induced by a complex dynamical evolution of their orbits that induced a 1:2 "*resonant crossing*" between the orbits of Jupiter and Saturn –this is the site where Jupiter completes two orbits about the Sun for every orbit of Saturn.

This resonant-crossing considerably enhanced the gravitational interactions between the giant planets, and within 100,000 years Uranus and Neptune were tossed outward while probably exchanging their orbits, and their gravitational sling effects destroyed a disk of "primordial" comets that was formed around the current location of these two planets. This did send bursts of comets throughout the whole solar system. A fraction of them could have formed the Oort cloud and the current EdK-belt, and a very small fraction did struck the terrestrial planets. About 97% of the comets were thus ejected and about 94% of the comets that struck the Moon arrived in the first 29 Myr. This was a very short pulse of impactors, which should have left a specific scar of impact craters on the Moon.

This model would nicely explain the invariance of the micrometeorites flux with times because it is likely that the mixture of dust grains that peppered the formation zone of cometary ice were formed at about the same time and in the same zone of the inner solar system. Consequently, all comets would have trapped a similar dust component (see Sect. 24.1) even though the contents of their "hypervolatile" species (CO and CH_4) greatly vary, by up a factor $\sim$20 for CO –see Mumma et al. (2005).

The current ratio of the orbital periods of the two planets is near 1:2.5. They are thus rather far from the 1:2 resonance. Therefore, the model postulates that the giant planets have since migrated to their present positions. In fact, the choice of initial conditions for the planetary system in this model is quite stunning and throws your mind out of the classical world that is still encrusted in our neurones since high school. Indeed, they assume that the initial orbits were more compacted, as the extension of the giant planets zones was two times smaller than today, and the disk of icy planetesimals was extending over a smaller range up to 30–35 AU. Moreover, Uranus and Neptune were formed between Jupiter and Saturn and the position of these two icy planets were inverted, as Neptune was first beyond Jupiter. This initial configuration lasted during a surprisingly long quiet period of about 600 Myr and then resonant-crossing was switched on.

The same resonant crossing would move Jupiter slightly inward (about a few tenths of AU) and this migration ejected about 90% of the asteroids that further fed the spike of lunar impactors. However, Gomes et al. point out the difficulty of estimating the flux of asteroids that struck the Moon (about 1–8 $\times$ 10^{21} g). Moreover, we further presented evidences supporting a minor role of asteroids –see Sects. 7 (3rd Subsect.) and 22.3 (last Subsect.). In this case, the spike model predicts that the impactors that struck the Moon included about 5×10^{21} g of comets delivered steadily over a time interval of 600 Myr before the spike, and about 9×10^{21} g of comets that struck the Moon during the spike.

The predictions of this spike scenario can be compared to those inferred in the most simple way from EMMA, where the total mass influx of impactors scales as $\Psi(t_1) \sim 0.1 \times \Phi(t_1) \sim 5.6 \times 10^{23}$ g. The total mass influx of comets on the Moon predicted by Gomes et al. (2005), which now includes the pre-spike value, is about 1.4×10^{22} g. The corresponding terrestrial value of about 1.8×10^{23} g is obtained multiplying this lunar value by the ratio of the cross sections of the Earth and the Moon of about 13. Now, the spike value is only 3 times smaller than that predicted by EMMA! Therefore, the misfit between the predictions of the two conjunctures for comets has been considerably reduced.

The extrapolation of our simple scaling law, $\Phi(t_1) \sim 10 \times \Psi(t_1)$, to the spike of comets would next imply that the swarm of the much more numerous comets, from which the spike was extracted delivered a total micrometeorite mass influx just 3 times smaller than the value deduced from EMMA. Such a misfit in "quantities" is just insignificant when so many different parameters are involved in both models. In fact, the major misfit between the models is not the mass influx anymore. It includes the severe deficit of the spike in small impactors capable of forming a megaregolith, and the large time delay for the delivery of their constituent water to the early Earth, which was required to form an early oceanic crust.

23.4 Hard Time on the Conjunctures

Comets cannot account for the "meteoritic" contamination of the lunar crust. The lunar wind generated by the impact of micrometeorites was depositing a contamination of Ir in the lunar crust of about 27–48 ppb –the lower and upper limits correspond to asteroidal and cometary micrometeorites, respectively. These values are 2–4 times larger than the "generally agreed" values measured by Kyte and Wasson (1975) of about 12 ppb. So the misfit, here is that micrometeorites delivered too much iridium to the lunar crust (see Sect. 21.1).

Let us estimate the specific Ir contamination of the crater forming bodies, which was previously expected to be the dominant Ir contribution in the lunar soil. In spite of 40 years of lunar studies, scientists are still reporting very different values for the so-called "meteoritic" contamination of the lunar crust, which is attributed to the fraction, η, of the initial mass, M, of impactors, which is retained by the lunar crust after impact, $M_A \sim M \times \eta$ (see Sect. 21.1). This yields estimates of M_A that range from about 5×10^{21} g to 8×10^{22} g up to $\geq 4 \times 10^{23}$ g depending on the choice of parameters selected by Ryder (1999), Sleep et al. (1989) and Hartmann (1980), respectively.

Gomes et al. (2005) give an additional estimate of the total mass influx of comets (i.e., including the contribution of the pre-spike component) striking the Moon of $M \sim 1.4 \times 10^{22}$ g, which would yield a value of M_A about 10 times smaller. The extrapolation to the Moon of the relationship, $\Psi(t_1) \sim 0.1\,\Phi(t_1)$, established for the Earth, yields another estimate of the mass influx of large impactors of about 4.3×10^{22} g, which is only 3 times larger than this value (see last section, last Subsect.). Both estimates would thus rather be compatible with the low value estimated by Ryder.

The lunar crust retains about 20% of the total mass influx of micrometeorites, but probably less than 10% of the mass of comets striking the Moon. Furthermore, only the dust component of comets, which represent about 20 wt.% of their mass (see Sect. 22.4, 3rd Subsect.) can deliver siderophile elements such as iridium. Consequently, if "cometary" micrometeorites delivered about 48 ppb of "retained" Ir to the lunar crust through the assistance of the lunar wind (see Sect. 21.1), the comets of the spike would have delivered a total amount of "retained" iridium about 100 times smaller, i.e., a value of ~0.5 ppb, which is smaller than the value (~1.3 ppb) observed in the most depleted "immature" soils.

Zahnle and Sleep (1997) already sensed the difficulty of only considering the contribution of comets to the delivery of siderophile elements to the lunar crust. They noted: like asteroids comets make basins, but for a given basin they leave much less iridium behind. In fact, this is not an objection anymore. Comets of the spike could have been responsible for these basins. But the iridium trapped in the lunar soil would have been mostly delivered by the interplanetary dust particles, which were released by the much larger number of comets that did reach the ice sublimation zone in the inner solar system. This is further supported by the discovery that comets are much more efficient dust emitters than previously thought, by up a factor of × 50 (see Sect. 22.3, last Subsect.).

We attempted to get further clues about the total mass influx of large impactors that struck the Moon, and/or their timing, while looking successively at:

- the spectacular multi-ring giant impact basins observed on the near-side of the Moon, from which Kring and Cohen (2002) inferred the total mass of material that struck the Moon during the spike;
- the thickness of the megaregolith on the lunar highlands, Δ_{lh}, which required an extensive cratering by impactors producing crater depths in excess of ~10 km (as to excavate fresh bedrock material that allows the growth of the regolith), and;
- very old Australian zircons;

The treacherous size distribution of the multi-ring impact basins. There are 196 and 45 impact craters with sizes larger than 100 km and 300 km on the Moon. When their sizes exceed about 300 km the craters develop a complex morphology of "multi-rings" basins. Kring and Cohen (2002) quote 12 post-nectarian multi-rings basins (i.e., formed after the Nectaris basin that occurred around 4 Gyr ago), which would have been formed during the spike of impactors. They estimate that the total mass of their parent impactors would be about 6.5–9×10^{21} g, assuming density of impactors varying from 3.3 to 1.2 g cm^{-3}, respectively. This value would remarkably fit the total mass influx of comets predicted by Gomes et al. (2005) of about 9×10^{21} g. Therefore, the validity of their spike scenario would be firmly established.

However, both the spike scenario and EMMA hit severe difficulties with the formation of these basins. The 8 most prominent impact basins visible on the near side of the Moon, are true single basins with sizes ≥800 km. There are still troubles determining their diameters and relating them to the explosive power of the impactors. One generally selects the diameter of the most visible of the outer rims. It does not correspond either to the smaller value measured for the basaltic lava that subsequently flooded the basins to form the Mare or to the initial diameter of the "transient" hole formed immediately after impact, and which was quickly partially filled by an isostatically uplifted compressed bottom.

You can see easily with a binocular the lava flows that form the superb lunar maria, but not the most visible of the outer ring of the basins. But you cannot be sure that the outer ring observed on a picture is really the last outer one. There are also some disputes about the choice of the ring that would correspond to the initial crater ring. Is it that of the most outer ring or rather that of one of the inner rings? The only reliable way would be to determine the total volume of the ejecta blankets and to relate it to the power of the explosion. But this is a tricky business too! Therefore, we just stick to the conventional view of assimilating the impact basin diameter to the most visible of the outer rings.

There are 88 craters larger than 100 km on the near side of the Moon, and the Maria are about 50 times less craterized than the surrounding zones. Therefore, the large craters mostly pre-date the formation of the oldest mare back to about 3.8 Gyr ago. As the Mare cover about 1/3 of the near side of the Moon, they eradicated about one third of the initial number of craters of about 130. The bombardment which produced the 8 basins with sizes ≥800 km, should have simultaneously formed a much larger number of ≥100 km craters, which are not observed. This difficulty was already noted by Wetherill (1981). It can be illustrated on a back of the envelope computation to evaluate the ratio between the numbers of craters with sizes larger than 100 km and 800 km, respectively. One has to rely on the observed cumulative distribution of the size, D_c, of impact craters, which is defined by a power-law characterized by an exponent, α:

$$N(\geq D_c) \propto (D_c)^{-\alpha}$$

where N is the number of impactors with a diameter greater than D_c, per unit of time (generally 1 Myr) and per unit area (this unit can astonishingly varies from 1 cm^2 to the whole lunar surface). On the Moon, photo geologists carefully avoid old surfaces, where the crater density has reached a saturation values characterized by $\alpha \sim 2$. Therefore, they rely on the basaltic flows that formed lunar mare younger than 3.5 Gyr. They also like to look at the cratered floors of young craters with a size of about 100 km, such as Copernicus and Tycho, where coveted distributions of fresh non eroded craters are still registered –these floors are about 850 and 100 Myr old, respectively.

To predict the effects of asteroids and comets on the D_c distribution one has to know about their size distributions measured by remote sensing and their relationship with the size distribution of the craters. Ivezic et al. (2005) and Levinson and Weismann (1999) reported the differential size distribution of asteroids and comets from the Kuiper belt, respectively:

$$N(R)dN \propto R^{-\alpha -1}dR$$

where R, is the radius of the body, and α is approximately similar to the index of the size distribution of impact craters. This major simplification results from the relationship between D_c and the energy, E, released during the explosion of an impactor with a radii, R, which was inferred from atomic and TNT bombs testing. It was found that the volume of the crater is proportional to E, and this translates into: $D_c \propto E^{1/\beta} \propto m^{1/\beta} \propto R^{3/\beta}$. With the "generally preferred" value of $\beta(\sim 3.4)$, D_c turns to be proportional to R. Therefore, one can replace D_c by R, and the exponent of the cumulative size distributions of asteroids and comets, which reads as $N(\geq R) \propto R^{-\alpha}$, also yields that of the size distribution of their craters.

Ivezic et al. (2005) measured the properties of about 13,000 asteroids in a study with the spectacular name of "SDSSCD" (Sloan Digital Sky Survey Commissioning Data). They discovered that the cumulative size distribution of asteroids gets steeper than previously thought beyond a radius, $R \sim 2.5$ km. For $R \leq 2.5$ km, $\alpha \sim 1.4$ (the previously revised value was about 1.8). But for larger sizes, the distribution gets much steeper ($\alpha \sim 3$). For comets, Levinson and Weismann (1999) note a slightly steeper distribution, with a values of about 2 and 3.5, below and above a radius of $\sim$10 km, respectively, which has still to be better defined.

Only craters with a diameter $\geq$100 km and a corresponding depth of $\geq$10 km, which are produced by impactors with a size $\geq$10–20 km, can generate a 10–20 km thick regolith, which requires an excavation of fresh bed rock material below the regolith. For such impactors, the new values of α are somewhat bracketed between 3 and 3.5. With these values, the ratios of the total number of craters with sizes $\geq$100 and $\geq$800 km, would be about 500–1500, for $\alpha = 3$ and 3.5, respectively. Therefore, the ratio of the total number of crater with sizes of $\geq$100 km expected from a spike of impactors that produced 8 basins with sizes $\geq$800 km would be bracketed between 4000 and 12,000! This huge number of $\geq$100 km size craters is just not observed on the near side of the Moon, which only shows 88 such craters outside the Mare, which correspond to an initial number of craters of about 130.

The mysterious origin of the giant basins. For asteroids, Wetherill proposed a kind of "ad-hoc" scenario as to reduce the proportion of small bodies in the spike of impactors that generated the impact basins. It involves the tidal disruption of a body with a mass of $\sim 10^{23}$ g. It was first locked in the long term storage zone of the Mars-crossing impactors, before being launch on Venus- and Earth-crossing orbits. Then it suffered a fragmentation during tidal interactions with one of the terrestrial planets around 3.8–3.9 Gyr ago, and the largest fragments generated the spike of multi-ring impact basins at about the same time. But the occurrence of this tidal disruption has been challenged, on the ground that the speeds of encounter do not allow a sufficient time of tidal interactions to trigger a fragmentation. However if a noticeable fraction of the comets are made of the extremely weak powder like material observed on comet Temple 1 (see A'Hearn et al., 2005), which is characterized by very low shear strength of 65 Pa (about 100 times smaller than the crushing strength of a friable HCC!), tidal disruption might becomes easier. Unfortunately, models of tidal disruption are all based, yet, on the propagation of the crack "tips" of fractures in solids, and they cannot be reliably extrapolated to the powdered material of Tempel 1.

Gomes et al. did not discuss this problem posed by the large impact basins on the Moon, but they collide right into it like EMMA. They deduced that the mass flux of comets that struck the Moon during the spike is about 9×10^{21} g. But this mass is already compatible with the single mass of the Imbrium impactor (about 4×10^{21} g). So, one can wonder naively how the roaming of Neptune throughout the precursor disk of the EdK-belt could have preferentially scattered out the largest bodies, leaving behind the much more numerous $\sim$10–20 km size comets? Or one should turn again to "Ad-Hoc" science to argue that the initial size distribution of comets at the time of occurrence of the spike, around 3.9 Gyr ago, was much flatter than today. A value of $\alpha \sim 1.5$ would then insure that "the mass of the single largest projectile is greater than the combined mass of all the smaller projectiles" (see Wetherill, 1975). Let us check whether the shape of the spike of impactors help improving this chaos in the understanding of the LHBomb.

A questionable clustering of the ages of lunar breccias around 3.85 Gyr ago. The date of occurrence and the spread in time of the spike of impactors were directly inferred from the distribution of the formation ages of lunar breccias. These ages measure the time at which radioactive parent/daughter ratios were perturbed by impact events. The distribution selected by Gomes et al. to constrain their model peaks at about 3.8–3.9 Gyr ago, and has a maximum width of $\sim$150 Myr.

But the distributions as yet reported have still no clear-cut interpretation. This is really a very tricky problem, and the difficulties have been clearly overlooked by some colleagues anxious to find a spike, which can be characterized with a word that delights the medias ("cataclysmic"). One has first to remember that none of the 6 Apollo and 3 Luna missions landed in a "pure" highland site. In fact they landed in and/or near an extensive "hot spot" with an anomalously high radioactivity (due to high contents of K, Th and U), coined as "PKT" (Procellarum KREEP Terrace) –see the wonderful WEB site of Randy Korotev (epsc.wustl.edu), which we did use to know everything about lunar meteorites. This odd feature was not known when the choice of the landing sites was made. But one already senses that any giant impactor that struck this zone could have peppered all the landing sites with breccias formed during this single impact. Is there any big multi-ring basin in it?

The Imbrium basin is right inside the hot zone. Furthermore, this is the largest youngest impact event that threw ejecta all over the near side of the Moon. Its age of about 3.85 Gyr is probably the best determined age of all lunar basins. One can be easily convinced about this striking power of contamination of the long range ejecta blankets of Imbrium just looking at the bright crater rays ejected much later on from the very young (∼100 Myr-old) Tycho crater. They can reach a distance of about 1500 km, but the crater is only 85 km wide! However, the power of the Imbrium explosion was about 2000 times larger than that of Tycho, and it came close to disrupting the Moon apart. As the volume of the explosion crater (i.e., the volume of the ejecta) scales as the energy of the explosion, just watch at the Tycho rays and multiply their number by 2000!

Therefore, if you collect rocks at random on the landing sites of the Apollo (A) or Luna (L) missions spread near the lunar equator, and close (A11, A16, A17, L16, L20, L24) or right in (A12, A14, A15) the PKT zone, you should find that they are mostly breccias enriched in K, Th and U. And their ages should peak around that of the Imbrium, of about 3.85 Gyr. This is just the case! For this reason, Larry Haskin (1998) argued repeatedly that the Imbrium ejecta loaded with breccias are widely spread on the lunar landing sites.

Wetherill already thoroughly discussed this problem. In particular, the best and least biased sampling of highland breccias collected during the Apollo 16 missions yields a distribution of ages (see Wetherill, 1975 and 1981; his Figs. 3 and 2, respectively) that does not fit the characteristics of the spike of comets predicted by Gomes et al. The peak around 3.9 Gyr is not prominent, and its width is more widely spread over ∼400 Myr. The steep raise of the spike in less than ∼30 Myr, which is one of the major prediction of Gomes et al. (see their Fig. 3b), is just not confirmed.

Moreover, even for a single event, the ages of the breccias would cluster in the ∼50 Myr range determined from various laboratories on the same rock! There are many other complications resulting from this biased "equatorial" sampling. In particular the giant impacts would be more effective at producing impact melt than smaller impacts, which would thus not be seen in the distribution. Furthermore, the recycling of the breccias in the larger amount of material heated up at a high temperature during the largest impacts, produced probably a range of ages even for a single impact. This strengthens the conclusion that the clustering of ages within a narrow time interval of 50 Myr might be produced by even a single giant impact and not necessarily by a spike of impactors with arrival times spread over a narrow time interval.

Wetherill (1975) reported on a numerical simulation, which takes into consideration the preferential destruction of old breccias (i.e., more than ∼4 Gyr old) due to the high impact rates. Starting with a population of exponentially decaying asteroids with a half-life of 70 Myr, he just almost perfectly matched an earlier experimental age distribution. The breccias older than 4 Gyr were mostly destroyed. Astonishingly, about 10% of the breccias with ages of ∼3.7 Gyr were also destroyed by the residual high impact rate! Now, this peculiar impact erosion of the breccias would produce an experimental peak in the distribution of their ages, which would fully support the existence of a high flux of impactors delivered by an exponentially decaying population of impactors prior to 4 Gyr ago! Grinspoon (1989) confirmed these deductions with a more elaborated model of the age distribution of surviving lunar rocks subjected to the high impact rates of a declining flux of impactors –see Hartmann et al. 2000; their Fig. 2. In this model, there is no late spike of cratering. The ages of the rocks are reset or the rocks are destroyed.

The lost spike of lunar meteorites. Cohen et al. (2000) made a clever move, measuring the formation age of lunar meteorites that are breccias. About 80 lunar meteorites were found on the Earth but some of them are “paired”, i.e., they result from the fragmentation of the same meteorite either during atmospheric entry and/or while they resided on Earth. One thus found 39 distinct lunar meteorites. With the exception of 5 small ∼1 cm size chunks of basalts, they are all impact breccias which are considered as sampling the whole lunar surface and not only the Apollo and Luna landing zones, which were under the firing range of Imbrium ejecta. Indeed, only one of them (Sayh al Uhaymir 169, with a high content of Th) would derive from the PKT zone. Consequently lunar meteorites would originate from outside this zone, and they should not be contaminated by Imbrium breccias. This sampling would thus eliminate the KTP Imbrium bias, which was probably still present in the distributions of ages compiled by Wetherill as a weak peak above background.

Larry Haskin would have just made the brief comment that the distribution reported in the Fig. 1 of their Science paper is not surprising at all. Indeed, there is no peak in this distribution, just a sharp drop off beyond ∼4 Gyr ago! Furthermore, the width of this distribution extends over 500 Myr! Consequently, the peculiar spike centred about 3.8–3.9 Gyr ago, with a width smaller than 100 Myr, has been lost. Now, the peculiar shape of their age distribution would rather well support both the massive destruction of breccias by high impact rates prior to about 4 Gyr ago and the end of the LHBomb that occurred around 3.2 Gyr ago.

While reading the book of Cassidy (2003), I further discovered that the 31 melt inclusions dated by Cohen et al. were extracted from only 4 of this set of lunar meteorites. Then, I got a little bit worried, because curators only distribute easily samples from large breccias, which were the best shielded against impact comminution. In this case they forward a biased selection of breccias to the investigators. Could it be that the analyses of melt inclusions from a few of the smallest and consequently most precious breccias in the lunar meteorites collection will possibly reveal the... lost peak?

23.5 Regoliths and Old Australian Zircons

An uncertain battle of exponent to describe the effects of impacts. Working on the effects of impacts requires using a set of power-laws of "something", each characterized by an exponent. Everybody starts with the basic power-law, which gives the cumulative size distribution of impact craters, $N(> D_c) = A \times (D_c)^{-\alpha}$, per unit time and unit of area (see previous section), where A incorporates the mass influx, ϕ_0. Unfortunately, beside the first exponent, α, you need other power-laws with their associated exponents. They end up combining with each others as to give more complex exponents. For example, Langevin and collaborators attempted to relate the thickness of the megaregolith on the lunar highland, Δ_{lh}, to the total mass influx of crater forming impactors $\Psi(t_1)$, since the formation of the crust at time, t_1 (see the quotation of their works, which was initiated in our group by Ceorge Comstock, in Sect. 3.4). The other exponents include: γ, which defines the cumulative mass distribution, $N(\geq m) \propto m^{-\gamma}; \lambda$ and λ', which relate the diameter and the depth of a crater to the explosive power of the impactor; a 5^{th} obscure exponent, χ, which is associated with the power law distribution of the thickness of the ejecta blankets formed upon impact.

In this kind of battle of exponents get ready to be the looser. You are constantly at risk of confusing the exponents and wrongly summing up, multiplying, dividing, deriving or integrating the power-laws. These calculations bear new complex exponents, which result from the combination of the five basic ones. This is not the end of the troubles. You might miss to add or subtract an anonymous number (i.e., 1) that has to be rightly inserted in the resulting set of complex exponents, when integrating of differentiating the new power laws. And what about confusing the symbols plus or minus, which have also to be rightly inserted in front of 1!

Or even worse, after hunting through a huge pile of papers, that kept you asleep for days, you finally find the "generally-agreed-value"(also coined as "the newer-consensus-value") of an exponent, such as $\delta = \gamma/\lambda = 2.04$. But you just discover ten second later that one of the more complex exponent that you build up with these two exponents, $(\delta - 2)^{-1}$, and which is used in the computation of the thickness of the thin regolith observed on lunar Maria (see below), just throw you to infinity because it reaches a value of 25! Then, to further increase the confusion, colleagues use different symbols for the same exponent. As you have not an unlimited supply of nice Greek letters that you can memorize, you end up generally using a given symbol to define different power laws or you can be as bad (or as desperate) as using a Latin or even a Chinese letter! Then, after a few days, as you can hardly understand Chinese, you loose the battle and you should quit the lunar cosmic firing range. But you are now addicted to the battle field, because its hold the secret of our distant past. Therefore, you move to the next battle field of exponents dealing with the growth of lunar regoliths, even though you are just in the deepest torpor.

Regoliths on the Moon. A ∼20 km thick megaregolith can only grow during the impact of bodies that excavate fresh bed rock material below the regolith. Thus, the craters have to be at least 10 km deep (this depth corresponds to crater diameter of about 100 km). The spike scenario cannot generate a megaregolith because the total number of ∼100 km size craters associated to the few large impact basins was not sufficient (see previous section, 2nd Subsect.).

Langevin investigated the formation of regoliths on the surface of Mercury, the Moon, the asteroids and Mars and its satellites with the other conjuncture of a declining impact rate also used in this book. The growth of a regolith can only last until the Moon gets fragmented upon a large impact that produces a crater with a diameter of about one lunar radius, R_M. This condition leads to an upper limit of the thickness of the regolith, Δ_f. An equation yields a value of $\Delta_f \sim R_M/45 \sim 40$ km. But this is such an intricate combination of exponents that there was little hope to report and print it correctly in this book.

However, while going through the numerous formula dispersed in these earlier studies, I found a little marvel of simplicity, which was intended to estimate the thickness of the thin regolith formed on lunar maria, $\Delta_{\text{Mare}} \sim 5$–10 m, since the end of the LHBomb, about 3.5 Gyr ago. During the revision of the proof reading of this book, at a time when I felt completely defeated by the more complex formula leading to Δ_f, I discovered that this simple formula still represents the best example of how treacherous the use of these various exponents can be.

The value of Δ_{Mare} was derived from the shape of impact craters, the relationships of their diameter and depths with the mass of the impactors, and the average mass flux of impactors that struck the Moon over the last ∼3.5 Gyr, of about $\phi_0 \sim 4 \times 10^9$ g per year, which was derived in the 1980's, (see Wetherill, 1976; Hartmann, 1980). The thickness of the regolith is obtained from the following differential equation:

$$\Delta^{[\delta-3]} \times d\Delta = k \times \phi_0 \times dt$$

where $\delta = \gamma/\lambda$. For lunar maria formed after the end of the LHbomb, back to about 3 Gyr ago, the cratering rate was assumed to be constant, and $k \times \phi_0 \sim 2.2$. One thus gets:

$$\Delta = k' \times t^{[1/(\delta-2)]} = 2.2 \times t^{0.7}$$

where Δ and t are given in cm and Myr, respectively. This astonishingly simple formula depends only on ϕ_0, the crater shape parameters and the value of the exponents γ and $1/\lambda$, which relate the cumulative mass flux of the impactors, $N(\geq m) = B \times m^{-\gamma}$, and the diameter of the crater, $D = C \times m^{\lambda}$, to the mass of the impactor.

The values of $\gamma \sim 1.3$ and $\lambda \sim 0.375$ used in this earlier model were given by Oberbeck et al. (1973) and Vortmann (1968), respectively, for impactors with mass $\geq 10^7$ g (corresponding to bodies with a size of about 50 m). And right away, this simple formula yields a thickness of about 6 meters for the mare regolith formed over the last 3 Gyr, which amazingly well fits the generally agreed measured values of about 5–10 meters. Moreover, with the same choice of exponents, Langevin predicted vastly different effects, which well fitted the corresponding observations. They deal in particular with the effects resulting from the combination of impact gardening with the irradiation of the lunar surface in fluxes of both solar wind ions, solar energetic particles and galactic cosmic rays, which have very different penetrations ranging from about 50 nm up to a few meters.

We tried to extend this formula to the LHbomb with the help of EMMA, just multiplying ϕ_0 in the differential equation by the relative lunar cratering rate, $K(t)$, reported in Fig. 1. One has then to integrate $K(t) \times dt$ since the formation of the lunar crust, at time t_1. In Sect. 8.3, we indicated that this integral reads as $K(t_1) \times \tau$, where $\tau = 70$ Myr is a reasonable value of the mean life of the swarm of impactors during the steepest decline of $K(t)$, which was already suggested by Wetherill (1975). We found that the thickness of the megaregolith on the highland is given by:

$$\Delta_{lh} = 2.2 \times \{K(t_1) \times \tau\}^{[1/(\delta-2)]} \sim 2.2 \times \{2 \times 10^6 \times 70\}^{0.7} \sim 1.4 \times 10^6 \,\text{cm}$$

This value of $\Delta_{lh} \sim 14$ km, astonishingly well fits the range of thicknesses proposed today for the highland megaregolith, which is about 15–35 km. Therefore, I was ready to stop right here, as to use a second time my powerful megaphone (see Sect. 7, 3rd Subsect., for the first historical use of the megaphone) to shoot that the reviewer who rejected one of our papers was very right, when he did claim that "EMMA is presented as a Panacea Universalis". Indeed, this scenario would account for an incredible variety of effects.

A devastating misfit with the previous "newer consensus" values of the exponents. Unfortunately, chaos did quickly smash my megaphone before I could use it. In particular, the value of ϕ_0 of about 4×10^9 g for the whole lunar surface, which was used in these earlier works, is similar to the corresponding terrestrial value subsequently deduced for the Earth from Os in deep sea sediments and deuterium in the oceans (see Sect. 7). Therefore, the corresponding value on the Moon would be about 13 times smaller. As the constant k' contains $(\phi_0)^{0.7}$, this decreases the thickness of the megaregolith to about 3 meters. This is not so bad as long as we trust our generous range of acceptable uncertainty (i.e., a factor 2–3).

The earlier values of $\gamma \sim 1.3$ and $1/\lambda \sim 2.7$ yielded the value of $\delta \sim 3.4$ that allowed getting this estimate. But meanwhile, the values of these two basic exponents have been revised to lower values of about 0.6 and 3.4, respectively –see Zahnle and Sleep (1999). With these values, $\delta \sim 2.04$, the exponent of $\{K(t_1) \times \tau\}$ just scales as $[1/(2.04 - 2)]$, and this trigger a cataclysmic increase in this exponent. It did reach a value of ∼25 that threw you to infinity when you want to account for a thin regolith with a thickness of a few meters. Just remember that we took the simplest formula as a case study!

On the right track with the last revision of the size distribution of ≥10 km size asteroids and comets? One can try using the formula $\Delta_{lh} = 2.2 \times \{K(t_1) \times \tau\}^{[1/(\delta-2)]}$ to estimate the value of the exponent, $1/(\delta - 2)$, which would yield a megaregolith thickness of about 20 km. We found a value of 0.82 that gives $\delta = \gamma/\lambda \sim 3.2$. The set of formulas given in the previous section (see 2[nd] Subsect.) shows that δ is equal to the exponent, α, of the size distribution of the impactors. Therefore, this exponent is much larger than the last revised value of 1.8.

Does this mean that this value is unreasonably high? In the previous section we reported that recent measurements of the sizes of about 13,000 asteroids (Ivezic et al., 2005) and the compilation of Levinson and Weismann (1999) dealing with the size distribution of comets in the EdK belt. In brief, for impactors capable of excavating material at depths ≥10 km, the values of α range from about 3 to 3.5. Surprisingly, the value inferred from EMMA ($\alpha \sim 3.2$), as well as the earlier value used by Langevin and collaborators ($\alpha \sim 3.4$) just falls within this range of experimental values (3–3.5). It looks like the thickness of the megaregolith might help constraining the value of α which is very difficult to measure in the EdK-belt.

This short tour in the treacherous world of exponents might help penetrating into the early impact history of the Earth and the Moon, while at least showing that these explosive exponents should be handled with the greatest care. One needs rigorous measurements of the size of asteroids and comets to constraints their values. After this exhausting battle in the cosmic firing range where the Earth and its baby Moon were exposed, let us turn to an unexpected constraint imposed on the conjunctures by the Jack Hills Australian zircons.

A stunning performance in microanalyses. In the Jack Hills formation old detrital zircons are shielded within pebbles preserved in more recent rock formation. Wilde et al. (2001) and Cavosie et al. (2004, 2005) developed a superb technique of microanalyses allowing working on up to 13 individual spots on a polished internal section of a single 200 µm sized crystal of zircon. Then, they are re-polished as to reveal new fresh internal surfaces that are further spot analysed, etc. Their dating with the U–Pb method, and the measurement of their oxygen isotopic compositions, involve using successively for the analysis of several internal surfaces of a given zircon, three distinct types of dedicated ion microprobes available in Australia, England and China!

The star in this exotic Jack Hills family of old Australian zircons, with an age of 4404 ± 4 Myr, carries the famous name of W74/2–36. A spectacular view of 3 of its internal surfaces is shown by Cavosie et al. (2005) –see the last 4 micrographs in their Fig. 7. Their formation required the existence of an early oceanic crust very soon after the formation of the Moon, around 4.4 Gyr ago, i.e., oceans of liquid water on a cool Earth around this date. This constraint is compatible with the predictions of EMMA, where about 90% of the ocean water whould have been formed during the first 100 Myr of the post-lunar period.

However, the delivery of water during the spike of comets, equivalent to a maximum global thickness of about 270 m, would have occurred too late (i.e., around 3.9 Gyr ago) as to account for the formation of this early oceanic crust. Gomes et al. predict that an additional amount of cometary water equivalent to about half this thickness was delivered before the spike, over a time span of about 600 Myr. In this case, a small amount of water equivalent to a thickness of 30 m did accumulate during the first 100 Myr period of the post-lunar period (with the wrong abundance of deuterium anyways). This looks insufficient to produce a widespread continental crust around 4.4 Gyr ago.

Back to the starting gate. A possible consensual alternative for the LH-Bomb would be a kind of composite picture of lunar impact history with episodic spikes being superimposed on the tail off of planetary accretion, which was already proposed by Hartmann (1980) and Wetherill (1981). As summarized by Weismann (1989), there is no reason to suppose that there was only one late spike of lunar impactors, and the last one “may have been preceded by several others, which are not easily discernable from it in the cratering record”.

In this case $K(t)$ might just turn to be the envelope that smoothes the successive contributions of a few spikes. As the number of impactors did decrease after each spike, this envelope looks as a kind of exponential decay. These spikes resulted most probably from bursts of planet migrations and not from the tidal disruption of a slow moving impactor. They look like unavoidable consequences of the existence of a debris disk of planetesimals around the early Sun that get “eroded” though an exchange of angular momentum with the planets. This decay would be mostly expected from comets of the EdK-belt, which is the largest swarm of planetesimals to be the most strongly affected by changes in the orbits of Uranus and Neptune. But additional spikes of Oort cloud comets could have possibly resulted from the interactions between the Oort cloud and its changing galactic environment including the dissipation of the stellar nursery in which the baby Sun was born (see Sect. 24.2).

It can be safely concluded that the only certainty about the uncertainties and controversies dealing with the early configuration of solar system in the making of $K(t)$ is that this curve might be the signature of a dominant role of comets. But their early configuration and the triggering mechanism that was firing them to the inner solar system still represent a vivid mystery of our distant past. Gomes et al. courageously quoted the exploration of their "available parameter space", which include free parameters in the initial conditions used in their virtual world of resonant crossing.

Future studies should help understanding the intricate network of problems discussed in this section. They include:

– the study of the dynamic of the dissipation of debris discs that should help shrinking this large available parameter space;
– the sampling of breccias collected on the floors of a few large lunar impact basins, which were thus shielded from the dominant contamination by ejecta of the late Imbrium impact;
– the analysis of the D/H ratio of the water of comets originating from the EdK-belt, and that might be isotopically lighter than that of the 3 comets from the Oort cloud as yet analyzed. In this case, the total mass influx of comets could be larger than about $0.1 \times \Phi(t_1)$;
– a better understanding of the propagation of SW-Ne and SEP-Ne in debris discs (see Sect. 24.3, last Subsect., for some explanation);
– the analysis of the cometary dust grains to be returned to the Earth by the Stardust mission;
– the collect of micrometeorites from the 1966 Leonid storm at Concordia

24 Micrometeorites and Early Solar System Processes

24.1 A Gigantic Conveyor Belt System of Dust Grains in the Solar Nebula

The constraint of grain sizes. The discussion presented in the last section suggests that Antarctic micrometeorites would dominantly originate from comets. However, they contain refractory inclusions made of refractory oxides (Fig. 46), abbreviated as CAIs (see Sect. 6.2), which can only be formed at the highest temperatures ($T \geq 1800\,K$) close to the early Sun. They are at least 10 times larger than the very small inclusions of refractory oxides (sizes of about 0.1–1 μm) observed in the most fine-grained SMMs belonging to the group of the chondritic–porous aggregates (see Zinner, 2004). In contrast, micrometeorite CAIs are smaller than those observed in CM-type HCCs (Gounelle et al., 2001), which are in turn about 10 times smaller than those observed in the "dry" carbonaceous chondrites (including the CV, CO and CK types), where they can reach a size of about 1 cm.

In spite of such large size differences, the isotopic compositions of oxygen in CAIs and refractory oxides from all these objects are very similar (Hoppe et al., 1995; Greshake et al., 1996; Engrand et al., 1999b). This similarity indicates that they were synthesized by the same processes in the same zones of the early solar system.

However, the CAIs of micrometeorites cannot form in this outer world of intense coldness where cometary ices were nucleated. Several arguments, including the formation age of two large CAIs from the CV-type chondrite Efremovka (Amelin et al., 2002), show that they were not imported from the interstellar medium. Therefore, they had to be formed in the immediate vicinity of the early Sun and subsequently transported to the outer solar system if micrometeorites are indeed cometary dust grains.

The same deductions hold for anhydrous silicates such as olivine and pyroxene, which are also considered as refractory phases, even though they form at slightly lower temperatures of condensation (~1500 K in the early solar nebula. Their oxygen isotopic composition measured for large crystals (~50–100 μm), medium-sized crystals (~10 μm) and very small crystals (0.1–1 μm) found in meteorites, AMMs and SMMs, respectively, are very similar (c.f., Engrand et al., 1998) –we do not consider here the rare interstellar

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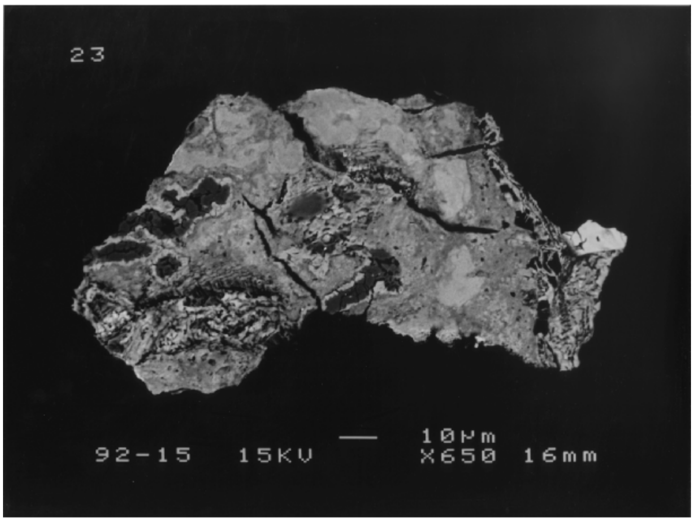

Fig. 46. Polished section of the fine-grained Antarctic micrometeorite 92-15-23 observed with a SEM, showing several calcium-aluminium rich refractory inclusions, poor in iron and appearing as the darkest phases observed in particular near the edge of the left-hand side of the micrograph. They are surrounded by a bright rind of an iron-rich variety of dehydrated serpentine (Courtesy of M. Gounelle).

silicates with an abundance $\leq$1%, which will be more appropriately discussed in the last subsect. and in Chap. 28. What is the meaning of the large size differences of CAIs and silicates found in SMMs, AMMs and carbonaceous chondrites?

An x-wind for a size-sorting of refractory phases. Recent models proposed for the formation of the solar system are based on the study of YSOs (i.e., Young Stellar Objects). In the model of Shu et al. (2000) these inclusions are indeed synthesized very near the early Sun, in a zone called the reconnection ring, which spreads up to about 0.06 UA. From there, they are ejected on ballistic trajectories by a powerful "x-wind" composed of huge surges of fast nebular gas. A severe size sorting is then expected.

The largest CAIs and silicates (both hydrous and anhydrous) fall back in the formation zone of asteroids where they sprinkle the future constituent material of carbonaceous chondrites. Only the smallest particles observed in micrometeorites can "fly" to the distant formation zone of cometary ices. In this way, even after a drastic perturbation of their orbits, which threw them out to their present-day reservoirs, these comets would still carry the same primitive initial mixture of primitive dust particles formed at about *the same time and in the same zone (i.e., in the inner solar system)*, even though their host ices might show different compositions (Mumma, 2002; Mumma et al., 2005). They would thus feed the interplanetary medium with a dust component that has an invariant composition over about the last 4.4 Gyr.

But we have still to find how and when these dust particles accreted into micrometeorites relying on panoply of processes such as aggregation in local eddies in the flow of the x-wind and the occurrence of a kind of regolith reprocessing of the cometary crusts triggered during the degassing of cometary nucleus.

The outdated "primitive" model of cometary nuclei. This does not exclude that the formation zone (s) of cometary ices could not be reach simultaneously by refractory interstellar dust grains (IS-dust) penetrating throughout the solar nebula, like today. Indeed, Grün et al. (2001), who initiated the measurements of their flux with micrometeorite detectors on board the Galileo, Pioneer and Ulysses spacecrafts, states that "most of the particles recorded outside 3 AU from the Sun have been identified as interstellar particles" (see his Sect. E).

Astonishingly, their mass flux is comparable to that expected in the local interstellar medium and their arrival coincides with that of the interstellar gas. Therefore, if a huge contamination of normal material made in the inner solar system was not reaching the distant formation zone of cometary ices, cometary dust should be mainly composed of interstellar dust grains. This would fit the conventional model where cometary nuclei are composed of the most primitive material.

McSween and Weismann (1989) already challenged this model about 15 years ago. Their works was ignored until recently, when it was further strengthened by the discovery of crystalline silicates (olivine and pyroxenes) in comet Hale-Bopp (Campins and Ryan, 1989; Wooden et al., 1999) –interstellar silicates are believed to be amorphous. Now, if we are right deducing that SMMs and AMMs are mostly cometary dust grains, they show very small contents of interstellar dust ($\leq$1%). This would imply that the bulk of the dust was made in the inner solar system in the first place in order to look isotopically "normal".

Still a few micro-CAIs and micro-chondrules in a few carbonaceous chondrites. Two observations seems to conflict with these predictions of the x-wind model. First, the unique group of the CR-type chondrites that are quite rare (about 0.05% of the meteorite falls) contains about 100 µm size and smaller CAIs. Thus, a minor fraction of small CAIs were deposited in the formation zone of CR chondrites. Moreover, microchondrules with sizes of about 50–100 µm were found in a few chondrites. However, only one such microchondrule (i.e., a rounded object distinct from cosmic spherules) has possibly been observed as an individual micrometeorite in the limited sampling of about 2500 AMMs investigated as yet by ourselves.

There is some agreement that a few carbonaceous chondrites might be cometary "rocks". They could have been ejected from either the mature crust of some extinct comets trapped in the asteroidal belt, or as pieces of rocks just lifted off more recently from the surface of active comets at heliocentric distance ≤2.5 AU (see last rubric in Sect. 22.3). Nevertheless, all these rare meteorites, including the CRs and the unique Tagish Lake chondrite, are still very different from AMMs at least with regard to both their very high D/H ratios (i.e., 1.35× SMOW for Tagish Lake) and their high content of chondrules in the case of the CRs.

We still do not fully understand how the conveyor belt system did not carry microchondrules in the formation zones of micrometeorites while it was simultaneously depositing micro-CAIs in the asteroidal belt. It could just happen that there was a cut-off in the size distribution of chondrules around 50–100 µm, right into the chondrule factory where they were made in the first place. Thus, there was no chondrule to be launched to the distant formation zone of cometary ices.

24.2 The Invariant Composition of the Micrometeorite Flux

The mystery of the invariant composition of micrometeorites might be rooted in the existence of a gigantic belt conveyor of refractory dust in the early solar system (see previous section) that sprayed cometary ices with the same dust component. It might also involve the general belief that the Sun was born in a small stellar nursery like most stars. It started to be qualitatively discussed since 1999.

It is mostly based on the observation that Oort cloud comets represent about 80% of the comets fired to the inner solar system today and the assumption that this proportion was invariant with times. Then, the micrometeorites flux would have been dominated by the dust component of these comets expected to have a rather homogeneous dust composition. But then, the population of the Oort cloud should have decayed with times accordingly to the lifetimes imprinted on $K(t)$ that increase from 20 Myr up to 200 Myr over a period of about 500 Myr.

There is a hint of an explanation in the brief quotation of Boyce and Huebner (1999) at the end of their Sect. VI, and in a few paragraphs in the books of Brahic (2000). Then Gladman (2005) gave references to related works published in 2000 and 2001. Brahic (2000) invokes a small nursery made of a few thousands stars. In this case, the half-lives of stars against dispersion by gravitational perturbation of their orbits can reach the "ad-hoc" value of about 50 Myr. Thus value would then steadily increase as the stellar nursery dissipates. Consequently, if the Oort cloud of comets did form in less than 50 Myr in the solar system, its constituent comets could have been gravitationally fired to the inner solar system by the nearest stars of the nursery, thus getting half-lives mimicking those of EdK-belt comets, up to the time when the nursery was dissipated. Then the normal sling effects of the giant planets took over, as described in the previous paragraph, continuing firing comets from the inner margin (30–50 AU) of the EdK-belt. Later on, the "normal" contribution of the Oort cloud as triggered by the motion of the solar system in the galaxy exceeded the declining contribution of the EdK-belt.

24.3 The Lost Record of High Dust Collision Rates in the Early Debris Disk

We find many puzzles during this short wandering in the early debris disk Sun, and most of them have still to be correctly addressed. In particular the dust density in the debris disk was much higher than in the contemporary zodiacal cloud with a total mass of about 2.5×10^{19} g –see Sect. 22.3, 2nd Subsect. Today the lifetime of a grain with a size, R (in μm), is dominated by the Poynting-Robertson effect, which spirals them to the Sun from 1 AU over a time scale of about $10^5 \times R$ (in yr) –see Burns et al. (1979). But if the dust density of the cloud increases up to about 30 times the present day value then the lifetime is dominated by grains collisions, and it gets much shorter.

In this case grain collisions should have markedly reduced the flight time of micrometeorites to the Earth and only a pure component of solar wind neon should have been stored in the grains (see Sect. 19). Indeed, SEP-neon, which is about 10^5 times less abundant than SW-neon, had no time to reach a concentration that could offset the saturation concentration of SW-Ne in the particles (see Sect. 19.3). However, about 60% of rocks from the upper mantle contain solar neon with ^{20}Ne/^{22}Ne ratios $\geq$11.2. It was likely injected during the subduction of a small fraction ($\sim$0.3%) of the flux of unmelted juvenile micrometeorites, back to about 4.4 Gyr ago (Sect. 19.5). Indeed, the average value of these solar ratios turns to be about 11.9, i.e., a value similar to that measured in Antarctic micrometeorites that have been flying recently in the contemporary configuration of solar system bodies, and which indicate a dominant SEP-neon component.

The apparent constancy of the neon isotopic ratio of both contemporary micrometeorites and rocks from the upper mantle loaded with solar neon would imply that after the formation of the Moon, the times of flight of interplanetary dust particles were not drastically modified. Therefore, a severe regime of grain collisions was not switched on. But then, how could we accommodate the much higher density of dust in the early debris disk, which is required to feed the intense post-lunar micrometeorite flux, which yielded the terrestrial atmosphere and overloaded the lunar crust with iridium? The neon "hobglobin" (see Sect. 19.3, last Subsect.) is probably still marauding somewhere in the debris disk, the Earth upper mantle and solar sunburns.

Part VIII

Challenges Ahead

We test the robustness of EMMA, during a kind of cross-examination of this scenario based on interesting questions and/or criticisms of colleagues. The three first sections deal with questions that have been almost fully answered only over the last year through the analysis of the Concordia micrometeorites collected in January 2002. However, our search for stardust in Antarctic micrometeorites described in Chap. 28 and problems gathered in Chap. 29 have still to be appropriately tackled.

25 Relationships with CM-type Chondrites

Colleagues still have trouble understanding how the dominant relationship between CM-type chondrites and AMMs was established. They also wonder about the meaning of this relationship in terms of solar system history, and they generally expect that it has been markedly altered upon atmospheric entry, except for the smallest particles collected in the stratosphere. They are also confused when hearing that in spite of strong similarities there are also marked differences between these two varieties of solar system materials. Consequently, some of them believe that this relationship has not been convincingly established. This section mostly relies on arguments already presented by Kurat and Maurette (1997) in a book published in French, which have only been improved recently through the analysis of the Concordia Antarctic micrometeorites (Duprat et al., 2003 and 2004).

25.1 The Primitive Chondritic Chemical Composition

Meteorites. In Sect. 6.1, we presented a classification of meteorites that singles out the three types of hydrous–carbonaceous chondrites (CI-, CM- and CR-type) as the most primitive meteorites. Among these HCCs, which amount to about 2.5% of the meteorite falls, the CI-type chondrites have best preserved the chemical composition of the atmosphere of the Sun (considered to be a chunk of the solar nebula), in spite of a devastating process of aqueous alteration effective in their parent asteroids, which transformed their initial mineral assemblage into a chunk of clays (c.f., Sect. 6.4).

An impressive feature of this primitive chondritic composition appears when the abundance pattern of the odd-atomic mass nuclides is plotted versus atomic masses larger than about 70. This pattern has a unique "zig-zag" structure, which is understood in terms of processes by which the elements heavier than iron were synthesized primarily by the capture of neutrons within stars and in explosive stellar environments. Any subsequent marked chemical processing of the CI material would have destroyed this pattern, which involves elements of widely disparate volatilities and/or cosmochemical affinities, including siderophile, lithophile and chalcophile elements –these elements have a chemical tendency to concentrate in metal phases, silicates and

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sulfides, respectively. Therefore, the accumulation of CI material in the solar nebula was probably a rather gentle, chemically undiscriminating process –see Cassen and Woolum (1999) for these important comments.

The meteorites that come next on this scale of primitiveness are the CM chondrites. The slight differences between the two types of material are illustrated in Fig. 47, where the red dotted line for Murchison refers to the abundance of a given element relative to that measured in CIs for 13 key major and minor elements, which have simply been ranked on a scale of increasing atomic number from Na to Ni. Among these elements, Ca and S are the most refractory and the most volatile of the moderately volatile elements (Mn, Na, Ca, S), respectively –on this scale of volatility the elements are ranked according to their temperature of condensation during the cooling of the solar nebula. They are currently interpreted as due to a stronger heating of the constituent material of the CM parent bodies, which produced a depletion of moderately volatile elements by up a factor 2–3, and a slight enrichment in the most refractory elements (Ca, Al, Ti, Ni).

Moreover, the third type of HCCs (the CR-type chondrites) is further depleted by an additional factor of about 2 in both lithophile (Mn, Na and K) and siderophile (Ga, Sb, Se and Zn) moderately volatile elements –see Krot et al. (2002); their Fig. 1b. All other meteorites, including the dry carbonaceous chondrites (CO-, CV- and CK-type) and the most abundant ordinary chondrites, depart from the CI-type chondrites while showing in particular a very strong depletion of C and N by a factor $\geq$10. Therefore, the composition of the CM chondrites is the least altered, relative to the primitive CI composition.

Cap-Prudhomme and Concordia micrometeorites. With the exception of volatile elements it can be expected that the one-time short pulse heating of a few seconds suffered by large AMMs that survive unmelted upon atmospheric entry did not significantly alter their chemical composition. This is supported by both:

– the simulation experiments of Greshake et al. (1998) that show that the non-volatile residual chondritic signature of CI chondrites is still preserved up to high temperatures near the melting point, and;
– the chemical composition of major and minor elements in fully melted micrometeorites (i.e., cosmic spherule) reported by Brownlee et al. (1977), who already wrote that "with the exception of volatiles and siderophiles, the average composition of the suite of cosmic spherules is most similar to CM chondrites based on the ratios of Mg/Si, Al/Si, Ca/Si, Ti/Si, Mn/Si and Fe/Si".

In the review of Jessberger et al. (2001), Kurat compared these CI and CM meteoritic abundances now plotted for 22 elements with those measured for the same elements in fine-grained and scoriaceous-type Cap-Prudhomme micrometeorites. He concluded that there is a close match between the

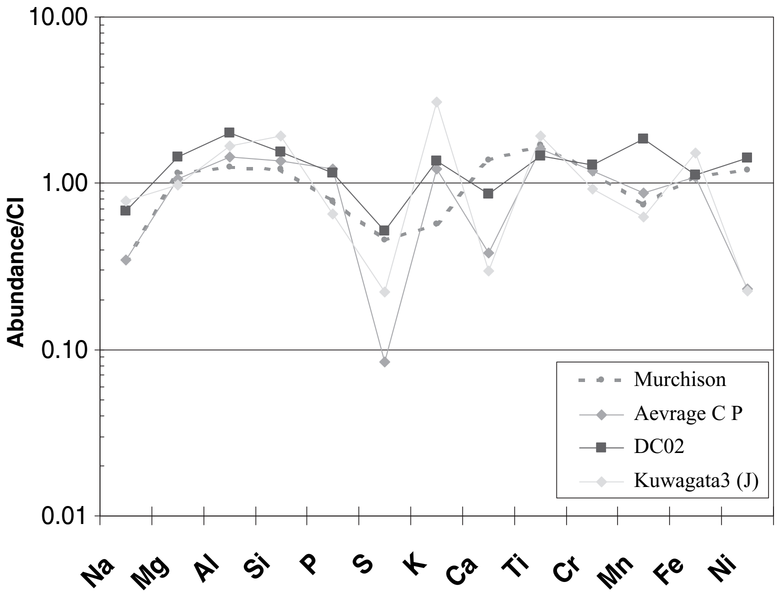

Fig. 47. Chemical composition of the Concordia micrometeorites (DC02) defined for 13 elements, and normalized to the composition of the CI-type chondrites. This composition is very similar to that of CM-type chondrites reported as the dotted line curve. It does not show any longer the strong depletion in S, Ca and Ni that was observed in micrometeorites collected in blue ice fields exploited at Cap-Prudhomme (CP) and in the Yamato Mountain range (Courtesy of C. Engrand).

composition of fine-grained CP-AMMs and that of CMs for the refractory elements (Sc–Cr, and Os and Ir). But the siderophile element abundances would be perturbed by the loss of soluble minerals (hosting Ni and Co) during cryogenic weathering (Kurat et al., 1992) and by terrestrial contamination (Au and As).

A comparison of Antarctic micrometeorites recovered from Cap-Prudhomme and the Concordia station confirmed recently the validity of this suspicion about the loss of soluble minerals and even helped in their identification (Duprat et al. 2003 and 2004). The abundance patterns (relative to CI chondrites) reported in Fig. 47 for the CP-AMMs were inferred from 13 elements, including only five elements of Kurat's plots (Na, K, Cr, Fe and Ni). However, they include four moderately volatile elements (Mn, Na, K and S) and four among the most refractory elements (Ca, Al, Ti and Ni).

In the CP-AMMs, only three elements (S, Ca and Ni) are strongly depleted. A very similar depletion was observed for AMMs collected around the Yamato Mountains by our Japanese colleagues. As Ca and S show the largest difference of volatility in this set of elements, their depletion can hardly be due to frictional heating, but rather to a cryogenic weathering that triggers a preferential dissolution of sulfides (carrying S and Ni) and calcium carbonates.

This could be confirmed only after the recent study of the Concordia micrometeorites, where this depletion is not observed anymore. This is explained by their remarkable shielding against cryogenic weathering (see Sect. 5.4) in their host very cold snow that accumulates in central Antarctica. The comparison of these abundance patterns clearly demonstrates that the composition of the CM-type chondrites best approximates that of the unweathered Concordia micrometeorites, if we recall that all other meteorites are strongly depleted in C and N. They also constitute a reliable signature of the pre-atmospheric constituent material of micrometeorites, and consequently of that of the dominant material existing in the interplanetary medium. The stumbling blocks are now to understand the provenance of this material and the causes of its unexpected dominance and invariant chemical composition.

25.2 Anhydrous and Hydrous Silicates

Anhydrous minerals. Presper et al. (1992), Kurat et al. (1994) and Gounelle (2000) already discussed the crystal "chemistry" of the constituent anhydrous minerals of micrometeorites, such as olivine, pyroxene, sulfide and magnetite. The composition of minor and major elements in each family of minerals is highly unequilibrated. This means that for a given mineral such as olivine the different crystals found in a given micrometeorite show different compositions (as indicated for example by variable Fe/Si ratios). This illustrates that the grains were not sufficiently heated up over an extended period of time to exchange atoms with their host matrix material through solid-state diffusion, in order to reach an equilibrium composition.

In spite of these variable compositions, each family of anhydrous minerals had a "fabric" in the early solar nebula similar to that of the corresponding mineral found in CM chondrites. For example, for olivine crystals, this similarity was established relying on:

- the "scatter" plot of the variation of the Cr_2O_3 content as a function of increasing FeO contents, which exhibit the same clusters of data points (c.f., Steel, 1992);
- the oxygen isotopic composition of olivine, which are similar in CM chondrite and AMMs (Engrand et al., 1999b) but different from that noted for the third subgroup of HCCs, the CR-chondrites (see Fig. 2 reported by Krot et al., 2002).

Hydrous minerals. The comparison between AMMs and CM chondrites looks more complicated when one focuses on hydrous silicates, where most of the constituent water of AMMs is locked. Indeed, minerals can be strictly identified from their crystalline structure as determined by X-ray and electron diffraction. But the initial crystalline structure of hydrous silicates, which is already quite disordered, is further degraded by the partial loss of water upon atmospheric entry. Therefore, it is difficult to identify their crystalline structure.

Nevertheless different methods allowed identifying saponite and serpentine as the major hydrous minerals of AMMs. Saponite contains both OH ("structural" water) and H_2O in its structure, while serpentine only shows OH. In 1990, Bruno Beccard identified these two types of water with an infrared Fourier transform optical microscope (Maurette et al., 1990). About 10 years later they were subsequently rigorously identified by our Japanese colleagues from both X-ray and electron diffraction patterns and direct TEM observations of the least disordered crystals that are relatively rare (about a few percent of the total number of hydrous silicates). Out of about 2000 AMMs they found 40 still well crystallized hydrous silicates where saponite was the dominant mineral. Saponite was also found to be the dominant hydrous silicate of SMMs (Zolensky and Lindstrom, 1992).

However, even after a loss of water that destroys their crystalline structures and prevents this direct identification, these two minerals can still be identified from their "relict" chemical compositions, as determined from "spot" chemical analyses of the fine-grained matrix of AMMs with an electron microprobe. This composition is still characteristic of these two important hydrous silicates, because saponite shows distinctively higher (Fe+Mg)/Si and Na/Si ratios than serpentine. By combining all techniques of identification, it could be shown that the CP-AMMs contain about 50% hydrous silicates dominated by saponite, whereas serpentine is the dominant hydrous silicate of CM-type chondrites.

This abundance of hydrous silicates is similar to that measured in CM-type chondrites. However the proportion of saponite which is the richest in water is higher in AMMs. This yields an average initial water content of AMMs of about 10%, which further supports their relationship with CM-chondrites that contain about 8% water. Indeed, the other CI- and CR-type hydrous–carbonaceous chondrites contain about 100% and 25% hydrous silicates, respectively. Moreover, all other types of meteorites are much drier.

The observation of the dominance of saponite in both SMMs and AMMs in a wide size range now spreading from about 10 μm to 200 μm is still a mystery, which again conflicts with all the predictions of the effects of frictional heating upon atmospheric entry, which are really inadequate (see also Sect. 22.2). Indeed, differential thermal analyses show that water is lost at a very low temperature of $100-200°C$ in saponite, whereas serpentine, which only contains structural water, dehydrates at higher temperatures of $700-800°C$. With such differences in thermal stability, only the crystalline structure of serpentine should have been detected after atmospheric entry in both SMMs and AMMs, and this is not observed. Indeed, saponite is the dominant crystalline phyllosilicate in both types of micrometeorites.

25.3 A Broad Distribution of Short Galactic Cosmic Rays Exposure Ages

There is a challenging observation dealing with the galactic cosmic rays ages (GCR-ages) of meteorites that was reported by Wieler and Graft (2001). The ages of the CI- and CM-type chondrites are much shorter ($\lesssim$5 Myr than those measured for all the other groups of meteorites (see their Fig. 4). Their wide distribution spreads between 50 kyr and 8 Myr, and shows a narrow peak at 0.2–0.3 Myr.

Morbidelli et al. (2005) further focused on the GCR-ages distribution of CM chondrites, taking into consideration new Antarctic meteorites, and they further confirmed the validity of this distribution. Oddly enough this distribution is quite comparable to that deduced for AMMs (c.f., Fig. 44) from their ^{10}Be contents (Raisbeck and Yiou, 1989). This similarity, which combines with the observation that micrometeorites are only related to these two subgroups of meteorites, should bear clues about the origin of the CIs and CMs and their relationships with AMMs.

It seems to support previous suggestions based on different types of observations (Lodders and Osborne, 1999), which suggest that CIs and CMs are not asteroidal but cometary rocks. Indeed, their short exposure would adequately fit the view that they were directly released at short heliocentric distance ($\leq$2.5 AU) during energetic outburst, allowing the lifting of rocks up to a size of 1 m from small cometary nucleus with sizes $\leq$5 km (Napier, 2001).

But the interpretation hits several difficulties. There is no reason why an approximately 100 kg rock such as Murchison (a CM-type chondrite), ejected from cometary nuclei, which was only subjected to gravitational perturbations, would have GCR-ages similar to that of 100 μm size cometary micrometeorites mostly subjected to non gravitational forces (i.e., the Poynting–Robertson drag and collisions with other dust particles). Moreover, in spite of marked similarities, there are also marked differences between micrometeorites and CIs and CMs, (see next Sect.). So, meteorites would hardly originate from the parent bodies of micrometeorites.

Another difficulty is that the cosmic ray exposure age of meteorites reflects the contributions of two distinct exposures, which are never clearly separated in review papers on this subject:

- the first one was acquired during the regolith history of the constituent grains of lunar breccias and gas-rich meteorites;
- the second one weighs the duration of the subsequent flight times of the meteorite to the Earth.

It is thus concluded that the cosmic-ray exposure ages reflect the flight times of meteorites in the interplanetary medium "*unless there is evidence for the contrary*" –you are wrong if you are thinking that this last quotation is from Pierre Dac. Nevertheless, this puzzling similarity of GCR-ages supports some kind of genetic relationship between these various types of hydrous-carbonaceous objects, which has still to be fully decrypted.

25.4 Major Differences between AMMs and CM Chondrites

Besides such strong similarities in chemical composition and mineralogy, there are also clear-cut differences between CM chondrites and large Antarctic micrometeorites. A major one, already discussed in Sect. 19.2, deals with the unique characteristics of micrometeoritic neon, as reflected by both its average content which is at least 10 times higher than the bulk values measured in HCCs, and its much smaller $^{21}Ne/^{22}Ne$ ratio (c.f., Fig. 39). These unique characteristics show at least that AMMs cannot be atmospheric break-up products of CM-type chondrites.

The other differences will not be discussed here. They encompass subtle differences in crystal chemistry (Kurat et al., 1994; Gounelle, 2000)). AMMs also show:

- a strong depletion of chondrules;
- a much smaller size ($\leq 10\,\mu m$) of their refractory inclusions;
- a 10–20 times higher pyroxene to olivine ratio that nicely fits the value determined from the telescopic remote sensing of the dusty tail of the Hale–Bopp comet (Wooden et al., 1999);
- a specific distribution of their D/H ratios that best fits the SMOW value of the terrestrial oceans, and which is different from those reported for HCCs (c.f., Fig. 21). They already imply that AMMs sample a new type of solar system material not represented yet in the meteorite collections (Engrand and Maurette, 1999; Maurette et al. 2000, 2001b; Jessberger et al. 2001). We next tackle the problem of the marked differences observed between the collections of stratospheric and Antarctic micrometeorites while penetrating with difficulties the hidden world of collection and sample processing biases.

26 The Enigmatic Differences between Stratospheric and Antarctic Micrometeorites

26.1 Chemical Composition and Mineralogy of SMMs

In Sect. 5.2, we quoted the excitement about tiny micrometeorites collected in the stratosphere (SMMs) with a collector plate coated with an approximately 100 μm-thick silicone oil layer, which was fixed under the wing of a stratospheric aircraft of NASA. As pointed out by Jessberger et al. (2001), *"due to contamination and collection limitations most of the SMMs have been limited to the 5 to 25 μm diameter range"*. Messenger (2000) describes these SMMs as: "diverse assemblage of materials, which are commonly very fine-grained (~0.1 μm), heterogeneous and rich in volatile elements and carbon relative to all meteorite classes".

The chemical, mineralogical and isotopic compositions of these SMMs have been investigated over the last 25 years or so (Bradley, 1988; Bradley and Brownlee, 1993; Rietmeijer 1998; Jessberger et al. 2001; Bradley 2004). They are considered to be made of a peculiar type of material presenting spectacular differences from both the most primitive meteorites and Antarctica micrometeorites collected at Cap-Prudhomme (CP-AMMs).

They have been classified into three major groups called hydrous–chondritic, anhydrous–chondritic and refractory. The chondritic ones are further divided into two additional classes to take into consideration their major silicates, either serpentine and saponite in the case of hydrous SMMs, or pyroxene and olivine in the anhydrous SMMs. Hydrous SMMs are generally compact whereas anhydrous SMMs are mostly highly porous –some hydrous SMMs have high porosities and, conversely, some anhydrous SMMs might be compact!

Porous chondritic SMMs (Porous-SMMs) are particularly unique while showing:

- a unique "fluffiness", which corresponds to highly friable aggregates of loosely bound particles with very small sizes (~0.1 μm) never observed before (see Fig. 4 in Sect. 3.2);
- large anomalies in the isotopic composition of their hydrogen and smaller, but still significant, anomalies in their nitrogen isotopic composition (see last Subsect. in this section);

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– the existence of a rich variety of radiation damage features, which is probably related to their more efficient cooling upon atmospheric entry (see Sect. 26.3), which would have preserved them from a rapid thermal annealing that occurs in silicates at low temperatures of about 600°C. They include:
– linear trails of radiation damage coined as tracks from iron group nuclei of solar energetic particles;
– amorphous coatings produced by implantation of high fluences of solar wind He, and;
– unique grains discovered by Bradley (1995), called "GEMS" (Glass Embedded with Metal and Sulfides), which are currently interpreted as interstellar dust grains. They were so heavily irradiated during their collisions with "superbubbles" of interstellar gas (Westphal and Bradley, 2004) that their crystalline structure was destroyed, switching to a metamict state resembling amorphous glass.

SMMs are found in the 5−50 µm size range and most of them are between 5 µm and 15 µm. However the silicone oil layer of the collector plate contains large SMMs that were crushed into tens to hundreds of particles upon impact (Fig. 48). They are known as "cluster" particles. Mike Zolensky, who is the

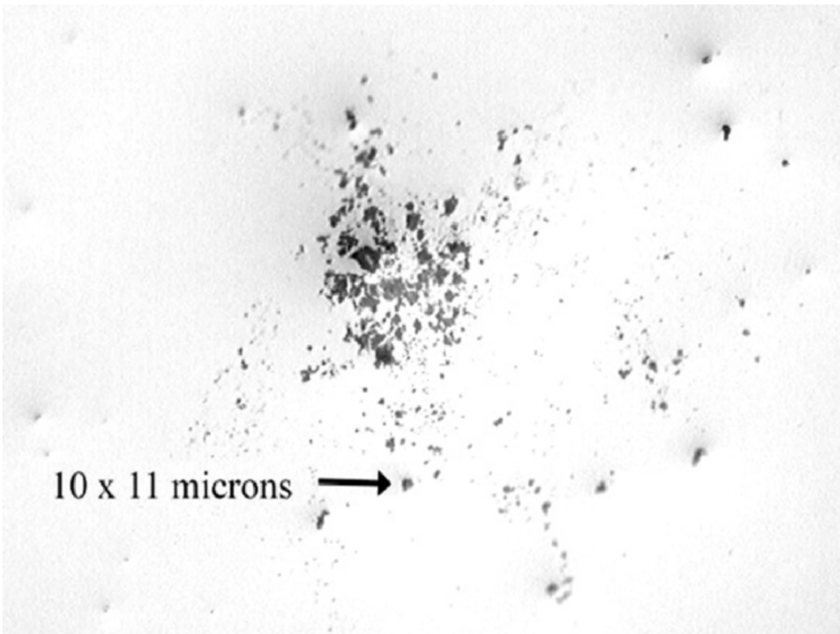

Fig. 48. A 200 µm size "cluster" chondritic particle collected in the stratosphere, which probably fragmented in the air turbulence induced very near the surface of the 300 cm^2 collector plates. This could produce a kind of spray of particles now trapped in the top surface of the 100 µm-thick oil layer (Courtesy of M. Zolensky).

curator of the IDPs collection of NASA, wrote that they are found in the top layer of the silicone oil layer. Consequently, they look like a kind of spray of particles, which were disaggregated possibly just before reaching the oil layer by the air turbulences that develop around any metallic plate flying at speeds of about 200 m/sec in the stratosphere. Their sizes in the oil layer give a range of apparent diameters of about 50−500 µm (see Bradley 2004, his Fig. 1d). However, the initial sizes of the cluster particles would rarely exceed 50 µm. The relative abundance of these cluster particles is poorly known. Bradley (2004) writes that they amount to about 10−20% of the particles.

The texture and mineralogy of the most abundant small SMMs and the cluster particles would be similar (Zolensky and Lindstrom 1992; Bradley 2004). However, the isotopic composition of hydrogen of the cluster SMMs show the highest D/H ratios ever reported yet in any extraterrestrial material, and which can reach about 50 times the SMOW value measured for an average of the terrestrial oceans (Messenger, 2000).

It has been argued that SMMs give the least biased sampling of the micrometeorite flux in the interplanetary medium because they suffered the least amount of frictional heating upon atmospheric entry. This is the reason for which they are still called IDPs. However, this word gives the wrong impression of their "intact" capture by the Earth. This is not correct. There are powerful radars nowadays such as the Arecibo 430 MHz incoherent scatter radar in Puerto Rico. Amazingly, they can detect sporadic micrometeorites in the 1 µm to 100 µm size range (Raizada et al., 2004). This detection shows that sporadic particles in this size range already release ablation gases that are necessary to form a wake detectable by the radar. They are not intact IDPs anymore. Consequently, they have been switched to the ordinary status of micrometeorites in this book.

Furthermore this deduction about the least biased sampling would be invalidated at least for the most numerous 5−15 µm particles, if they are truly different from the larger interplanetary dust particles with sizes of 100−200 µm, which are responsible for the dominant mass fraction of extraterrestrial material accreted by the Earth (Love and Brownlee, 1993), and that best overlap the size range of AMMs. In this section we argue that the Concordia collection of AMMs, and not SMMs, gives the most representative sampling of the micrometeorite flux before atmospheric entry even though they were more strongly heated up.

26.2 Differences with the Cap-Prudhomme AMMs

From fluffiness to chemical composition. During more than a decade we could only compare SMMs to the Cap-Prudhomme AMMs (CP-AMMs), noting in particular that CP-AMMs show:

– a lack of genuine fluffy and friable particles;

– larger sizes of their constituent grains;
– a strong depletion of S, Ca and Ni relative to CM-type chondrites;
– much smaller D/H ratios;
– a much more frequent and homogeneous thin magnetite shell that encapsulate the particles;
– the absence of carbonates and sulfates that are abundant in SMMs;
– the lack of radiation damaged features; etc.

In these earlier times, the smallest size fraction of CP-AMMs recovered was between 50 µm and 100 µm, whereas most SMMs had sizes bracketed between 5 µm and 15 µm. The larger size of AMMs induced their stronger heating upon atmospheric entry, which partially dehydrated their hydrous silicates (see Sect. 25.2) and could have led to the compaction of any texture similar to the spectacular fluffy structure of SMMs (Fig. 39). Moreover, at Cap-Prudhomme, a mechanical pump was used to vacuum up the glacial sand deposited on the bottom of the pocket of melt ice water (see Fig. 6). Unavoidably the most friable particles were destroyed during this pumping operation.

With regard to the depletion of S, Ca and Ni observed in the CP-AMMs, we note here that these elements were leached out during "cryogenic" weathering effective on particles exposed to the solar thermal wave in the top layer of the blue ice fields, which was described in Sect. 5.4 (Moving to Concordia to avoid cryogenic weathering). This process was already known to affect all chondrites collected on stranding blue ice fields near the Transantarctic Mountains, transforming their FeNi inclusions into rust grains down to the centre of the meteorites. Size differences also affect the lifetimes of the particles in the interplanetary medium against destructive collisions and/or the Poynting–Robertson drag. Small and large micrometeorites could thus originate from different parent bodies.

Therefore, differences between SMMs and AMMs were first attributed to these different sizes and conditions of weathering. Moreover, the Earth accreted these two distinct sets of micrometeorites at different epochs. At Cap-Prudhomme, AMMs were extracted from a flow of ice that took about 50,000 years to reach the margin of the ice field, while SMMs correspond to micrometeorites delivered to the Earth over the last 25 years or so. For this reason Messenger and Walker (1998) suggested that SMMs sample recent particles injected in the inner solar system by comet Schwassmann–Wachmann 3.

But we found a crossover in the size of SMMs and CP-AMMs when we collected for the first time in January 1991 the 25−50 µm size fraction of the glacial sand of Cap–Prudhomme, from which we extracted small AMMs. Micrometeorites from this size fraction were subsequently investigated with Brownlee (Maurette et al., 1992) and by Gounelle and collaborators (2000, 2005). We still found major differences between both collections, which cannot be accounted for anymore by size differences.

26.3 The Isotopic Puzzle

One of these major differences deals with the isotopic composition of hydrogen and nitrogen. The distribution of the D/H ratios of SMMs is the widest ever reported (Fig. 49) with a "maximum" value found in the famous SMM nicknamed "Dragonfly", which is about 50 times higher than the SMOW value (Messenger, 2000)! This distribution yields an average value of the D/H ratio of SMMs about 1.8 times higher than SMOW (i.e., an enormous difference in isotopic geochemistry), which is comparable to the high bulk values measured for cometary water (about 2 times SMOW) and unequilibrated chondrites (mostly the LL3- and CR-type showing whole rocks average ratios of about 1.8 and 3.5 higher than SMOW, respectively; see Messenger, 2001).

About half the SMMs show $^{14}N/^{15}N$ ratios that are also higher than the terrestrial standard value (measured for atmospheric nitrogen), but the maximum value of the $^{15}N/^{14}N$ ratio is "only" about 1.4 higher than the reference value. Nevertheless, the corresponding excesses of ^{15}N observed in about half the SMMs are still considered to be large and significant in isotope geochemistry.

It is generally assumed that the carrier phase of these anomalies is the carbonaceous component of SMMs. Indeed, only ion–molecule exchange reactions at low temperature in cold molecular interstellar clouds can produce such high ratios (Zinner, 1998). The $^{13}C/^{12}C$ ratio should be simultaneously

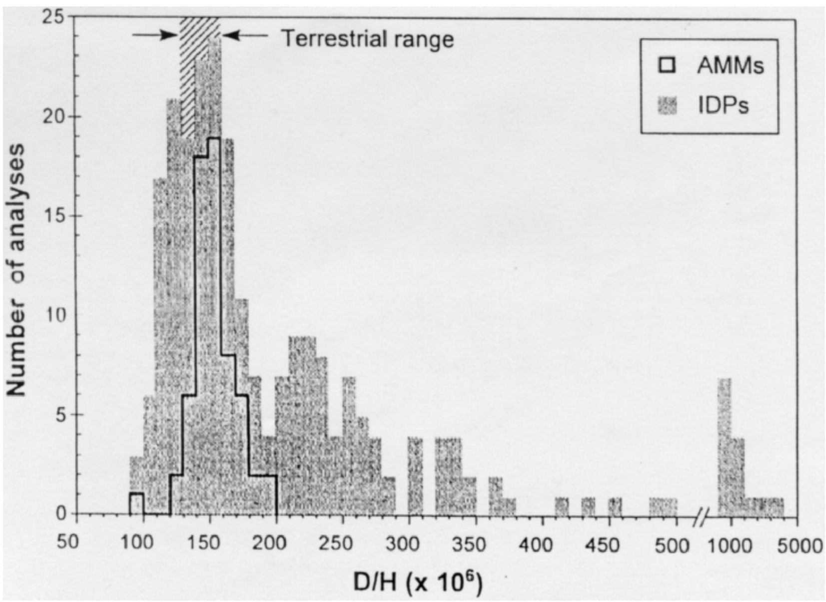

Fig. 49. Distribution of the D/H ratios measured for stratospheric micrometeorites, which is presented and discussed by Engrand et al. (1999a).

affected by these ion–molecule reactions. Oddly enough, its values in SMMs are rather similar to the reference value measured in terrestrial carbonates! This "anomaly-within-anomalies" is unexplained, yet.

Contrarily to the Moon, the Earth retains all the material of the incoming micrometeorite flux, including their volatile species mostly released upon volatilization and melting during atmospheric entry, when the carbonaceous component of micrometeorites is degraded into N_2, H_2O and CO_2. Consequently, if SMMs give a truly representative sampling of the dominant flux of juvenile micrometeorite with sizes of 100–200 µm in earlier times, the Earth's atmosphere should show a much higher D/H ratio and a significantly higher $^{15}N/^{14}N$ ratio. This is not observed.

Instead, the SMOW value turns to be similar to that deduced for the constituent water of the hydrous silicates of AMMs –see also Sect. 29.5. This implies that the carbonaceous component of juvenile micrometeorites, which was released as N_2 and H_2O in the early atmosphere, did not carry the large hydrogen and nitrogen isotopic anomalies observed in SMMs. This preponderance of the contribution of large "normal" micrometeorites is also independently supported by the D/H ratios of the "fossil" micrometeorites with sizes $\geq$100 µm, called microclasts, which are trapped in the matrix of the Kapoeta achondrites (see Fig. 5 in Sect. 10.1). Their average D/H ratio is similar to the AMMs value (Gounelle et al., 2003). While questioning over the last decade the origin of these huge differences between SMMs and AMMs, we found that they are likely related to an astonishing cascade of complementary biases between the two collections of small and large micrometeorites.

27 The World of Hidden Biases: From Collection to Sample Processing

Any study of micrometeorites involves a variety of biases, which start right away during their collection, and which have not been sufficiently publicized. This section deals with the astonishing folklore of these biases. We shall question whether major differences observed between Antarctic micrometeorites and stratospheric micrometeorites could reflect kinds of complementary biases between the two collections of micrometeorites. Astonishingly, some of them would converge to enrich the SMMs collection in the most fine-grained fluffy dust particles accreted by the Earth. They might be possibly the most primitive material accreted by the Earth. But they would not give a representative sampling of the bulk micrometeorite flux, which is best obtained with the new Concordia micrometeorites collected in central Antarctica. For a change, biases developing around a small metallic plate flying at ∼200m/sec in the stratosphere turned out to be quite helpful!

27.1 Biases in Greenland and Antarctica

Biases in Greenland and Cap-Prudhomme, Antarctica. Micrometeorites have to be handpicked with appropriate tools, under a low magnification optical microscope, from a high background of terrestrial dust grains. It is already very difficult to avoid making a biased selection of them during this operation.

Unfortunately, this first bias is only one among many. They are rooted in causes as diverse as:

– the totally diverging interest and/or previous training of the research groups;
– the use of different elements to normalize chemical analyses, which can thus hardly be compared, such as silicon, iron (and nitrogen in our own studies of volatiles);
– the laziness to consider that each tiny micrometeorite with a mass of a few μg might be a unique object, which has first to be split into several fragments in ultra-clean conditions, in order to save some of them for future analyses requiring very different preparation techniques if they turn out to be exceptional objects;

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– a highly biased selection of grains with the hope of finding the most exotic ones that might be quite rare, and which will insure the publication of a paper in "prestigious" journals (this ambition is never clearly stated by the investigators).

We know that such exotic particles do exist, but we still do not know how to pre-select them. For example, imagine a micrometeorite that would be loaded with very high content of carbonaceous matter such as the Japanese TO440033 fly-ash looking particle called pseudo-micrometeorite (Osawa and Nagao, 2002) and a Cap-Prudhomme micrometeorite made of pure ferrihydrite, which was lost during a poor sample handling in another laboratory, with the exception of a tiny fragment used to infer its extraterrestrial origin from features such as the thin magnetite shell formed upon atmospheric entry (c.f., Fig. 32 in Sect. 13.2).

We started our first work on micrometeorites in 1984 making right away a biased selection... of Greenland micrometeorites. We were probably too impressed by the spectacular fluffiness of SMMs that we observed with the greatest amazement when we visited the laboratory of Brownlee before our departure to Greenland. Therefore, we preferentially selected in the new set of large ($\geq$100 μm) unmelted Greenland particles those that looked at first glance to be the fluffiest and most porous ones, and therefore the best preserved micrometeorites in the new collection.

In fact, they ended up belonging to the scoriaceous type AMMs (see Fig. 15-8, in Sect. 6.3), i.e., the micrometeorites that were the most strongly heated up upon atmospheric entry while still escaping complete melting, as they still contain intact refractory phases such as anhydrous silicates and CAIs, as well as a high content of solar neon! They look quite fluffy because they are loaded with vesicles formed during the loss of volatile species. Moreover, at Cap-Prudhomme, the most friable particles were destroyed in our pumping system. Therefore, we added a "pumping" bias to the friendly world of collection biases.

A colleague recently created a spectacular sample processing bias, which deserves an entry in the Guiness book of world records. He succeeded ruining a whole daily collect of CP-AMMs, including more than 2000 AMMs, which we lent to his home Institution for preservation for future generations! He embedded all micrometeorites in epoxy resin mounts –except those of the $25-50$ μm size fraction that were "too small" to be easily extracted from their host sand! All mounts were polished, and right away at least one third of the material of each micrometeorite was lost as the sections were cut throughout the grains. But even worst, their epoxy resin "coffin" is made of one of the dirtiest materials around, which has the amazing ability to permeate all micropores and/or microfractures. Therefore the whole collection has been ruined with regard to many important analyses, which can only be made on the cleanest, least contaminated micrometeorites!

This chaotic trip into the frustrating world of hidden biases was fortunately interrupted last year (at least momentarily) by the preliminary analysis of the new set of AMMs collected near the Concordia station in central Antarctica (Duprat et al., 2003).

Minimizing biases with snow from central Antarctica. In 1996 we realized that in central Antarctica the conditions of collection should be very different. Any fresh snow gets steadily buried by precipitations of tiny snowflakes occurring at an average rate of about 3.5 cm/yr of water equivalent near the French–Italian station Concordia (as snow is less dense than water this corresponds to a thickness of snow of about 8.5 cm/yr). At a depth of about 100 m the compressed and cold snow is transformed into solid ice, which starts to slowly move to the seashore, where it will form blue ice fields near the margin and icebergs.

Fresh snow collects everything "falling" from the sky" at free fall velocities. Therefore, an approximately 25 cm-thick slab of snow sliced at a depth of about 0.5 m, in January 2002, collected micrometeorites that felt on the Earth in 1999, 2000 and 2001. These AMMs spent at most a month on the top snow surface. They were constantly kept in deep freeze conditions in a much colder and drier environment than at Cap-Prudhomme. Therefore, they were very efficiently shielded from the process of cryogenic weathering. Consequently, Concordia-AMMs might not show the high depletion of S, Ca and Ni relative to the CM-type composition observed in CP-micrometeorites (see Sect. 25.1).

In January 2002 the soft collection system built by Jean Duprat allowed the discovery of highly friable fine-grained micrometeorites, never recovered before from Antarctica –c.f., Sect. 5.4 and Fig. 35 in Sect. 16.1. In this system, there is no pump and/or fast flow of water throughout pipes, which always fragment friable particles colliding with obstacles such as the mesh of a sieve. The system reduces to a gentle gravitational siphoning of melt snow water through a single nylon sieve. Furthermore, the "impact" of AMMs with the soft snow at free fall velocities ($\leq$10 m/s) is much less destructive for any kind of particles than the impact speeds of about 200 m/s on the SMMs collector plate. Furthermore, the harder and large particles do not bounce back to space.

Therefore, the proportion of fine-grained unmelted micrometeorites with sizes $\geq$100 µm is about twice as high as at Cap-Prudhomme, thus reaching a value of about 25% and about half of them are now very friable. We recall that about 25% and 50% of the remaining micrometeorites collected in the snow are scoriaceous-type AMMs and cosmic spherules, respectively. Moreover, the Concordia micrometeorites do not show the depletion of S, Ca and Ni observed in CP-AMMs and their chemical composition is now very similar to that of the CM-type chondrites (see Fig. 47 in Sect. 25.1).

Working in ultra clean conditions in a trench to collect a very clean snow (see Fig. 45 in Sect. 22.4), at 1000 km from the seashore, on top of an approximately 3.2 km-thick layer of clean ice, considerably decreased the proportion of terrestrial dust grains in the Concordia collection to less than 50% ! The high purity of this collection is unsurpassed, yet, even in the SMM collection. It adds to other features to make the Concordia collection the least biased collection of large (≥50 μm) micrometeorites, which best sample the dominant mass fraction of the contemporary micrometeorite flux around a size of about 100 μm.

In particular the low abundance of terrestrial grains allows handpicking all the grains on the filter, and processing them in the same way. One fragment of each grain is thoroughly examined with a scanning electron microscope (SEM) equipped with an X-ray spectrometer. This allows minimizing the risk of rejecting truly extraterrestrial particles during either the pre-selection of dark charcoal-looking particles or their subsequent analysis intended to only select the fragments showing a chondritic composition.

Until June 2004 we made the usual pre-selection of the grains with the optical microscope. Then, we investigated with the SEM all the particles from the left over residue of the Concordia collection and first found that about 10–20% of them had still a chondritic composition and should thus be classified as extraterrestrial particles! Moreover, besides the chondritic composition, we could also apply other criteria to further identify extraterrestrial particles among those showing a non-chondritic composition (there might be lunar and Martian micrometeorites in the AMMs collection).

27.2 A Preferential "Skimming" of Fine-grained Primitive Dust in the Stratosphere?

Biases in the stratospheric collection. Collection and sampling biases were unavoidably made in SMM studies. For example, a well-known distribution of their carbon contents was discussed in the reviews of Jessberger et al. (2001) –c.f., Fig. 14 in this paper– and Bradley (2004). It was frequently used to argue that the carbon content of SMMs is at least twice as high as (≥10 wt.%) that of the most carbon-rich meteorites, the CI-chondrites. It would nicely fit the high carbon contents detected in the grains of the dusty tail of the Halley comet, thus giving a powerful hint that SMMs could be cometary dust grains. It is unavoidable that a biased selection of the best-looking particles was made during this investigation. Therefore, there is still no accurate value of the average carbon content of a truly random choice of SMMs. About another example of biases, it was said that SMMs "*looking to be melted*" were eliminated from the selection.

The anomalous lack of scoriaceous type micrometeorites in the SMMs collection. SMMs impacted the thin film of silicone oil spread on the metallic collector plate at speeds of about 200 m/s. Then, they had to be extracted from the silicone oil with a micromanipulator, and rinsed with freon and/or hexane to dissolve the oil. As the collector plate was rapidly coated during the stratospheric flight with a layer of sulfuric acid aerosols, some of the SMMs could hardly avoid being contaminated with S and Br while penetrating though this layer. One can already sense that biases are all around during a stratospheric flight. However, what are they?

About 15 years ago, we already noted the anomalous lack of scoriaceous particles ("scorias") and chondritic barred cosmic spherules in the SMMs collection, and this was the first hint about a strong bias in this collection. We recall that scorias are just fine-grained hydrous–carbonaceous micrometeorites (see Fig. 15 in Sect. 6.3) that got more strongly heated up during atmospheric entry in the thermosphere, i.e., well above the flight altitude (∼20 km) of the stratospheric aircrafts. They are quite hard and do not easily fragment.

These scorias have now been observed anywhere, any time, and in any size fraction (from 25 µm upto 800 µm) in all AMMs collections, including the new Concordia collection. In the 50−100 µm size fraction the relative abundances of scorias, unmelted micrometeorites and cosmic spherules are about 40%, 40% and 20%, respectively. Recently, Gounelle et al. (2005) observed similar proportions of scorias in the 25–50 µm size fraction. They should have been found in the SMM collection, which now contains cluster particles with initial sizes of up 50–100 µm.

Unexpectedly useful collection biases in the stratosphere. The surface snow at Concordia collects everything "falling from the sky". However, a cubic meter of stratospheric air is already very much enriched in the fluffiest low-density micrometeorites with small gravitational settling speeds. They will be overconcentrated in the $\sim 10^5\,\mathrm{m}^3$ of stratospheric air, which will be swept by a $300\,\mathrm{cm}^2$ collector plate during the typical flight of a stratospheric aircraft. However, the hard denser scorias will be already depleted because their higher density induces higher settling speeds.

Moreover, other processes also contribute to deplete the SMMs collection in scorias. Micrometeorites are carried by the airflow turbulences, which develop around the collector plate. As first noted by Gounelle (2000), the "flight" parameters of the particles, mostly related to their external shape and smoothness, thus play a role. Indeed, the particles that are the best coupled to these turbulences will preferentially stick to the approximately 100 µm-thick layer of silicone oil spread on the collector plate, which is fixed under the wings of the stratospheric aircraft to be parallel to the flight direction.

This is the case of the fluffy SMMs showing the highest specific area and the smallest constituent grains, which are generally sparsely coated with the thin magnetite shell. The beautiful SMM reported in Fig. 5 does not show any evidence for such a shell, which would considerably smooth their external surface. In contrast, scorias show the smoothest surface of all the unmelted micrometeorites, not only because their habit is already quite rounded but also because they are the particles showing the best developed thin magnetite shell –see Figs. 27 and 28 for the natural and artificially made shell observed around a scoria and a fragment of Orgueil pulse heated up in a Martian type atmosphere. Therefore they are loosely coupled to the air turbulences and their sticking efficiency should much smaller than that of a fluffy fine-grained SMM.

There might be another efficient collection bias already effective in the air turbulences produced around the collector plate. Mike Zolensky wrote that *"Our experience is that the cluster particles are not present thought the entire column of oil. They float near the surface"*. Now suppose that the most friable particles that are not mechanically shielded within a magnetite shell are disaggregated in the air turbulences that unavoidably develop around the collector plate and that preferentially drag them to the plates –they could also have disaggregated while crossing the sulfuric acid aerosol layer deposited on top of the silicone oil layer.

Could they burst near the plates while spraying the top surface of the silicone oil layer with their fine-grained constituent particles? If the bursts occur very near the plate the particles cannot fly too much apart and they form a cluster. However, if the burst is more distant from the plate the spray will spread on a larger area and its constituent particles will look like normal *individual* tiny SMMs. This bet would be comforted by the observation that the small and big SMMs are similar (see Sect. 26.1) but different from Antarctic micrometeorites. This might also explain why only a few SMMs show a magnetite shell, as they would be fragments from the external surface of the larger cluster particles.

Astonishingly, these "flight parameter" biases would be further amplified by a kind of feedback process. Radiative emission is the most important process to cool down the incoming particles and limit their frictional heating. It is more efficient, not only for small micrometeorites already showing a high surface to volume ratio, but at a given micrometeorite size, for micrometeorites composed of the smallest grains, which increase the radiative emission of their external surface. This hinders the formation of the magnetite shell, which in turn would smooth the external surface of the particles, thus decreasing their coupling to the turbulent airflow and their probability of sticking to the silicone oil layer.

Unexpectedly, all biases would work toward preferentially extracting from the micrometeorite flux only the most fine-grained and most friable particles, which might be the most primitive micrometeorites! If they turnout to originate from big friable particles that burst in the air turbulences before hitting the silicone oil, how could such larger parent particles survive upon atmospheric entry? Could they be delivered by chunks of extraterrestrial ices impacting the upper atmosphere? Anyways, for a change, collection biases turned out here to be quite helpful!

However, SMM-type particles should be relatively rare in the micrometeorite flux and they would not be representative of the bulk micrometeorite flux, which is mostly delivered by approximately 100 μm size particles. Love and Brownlee (1993) observed that before atmospheric entry, the mass fraction of the micrometeorite flux in the 5–15 μm size range represents less than about 1% of the micrometeorite flux. This is further confirmed by the D/H and $^{15}N/^{14}N$ ratios of the atmosphere that are much smaller than the values measured in SMMs and could not thus originate from a juvenile micrometeorite flux dominated by SMM-type micrometeorites. Therefore, their contribution to problems such as the formation of the atmosphere and the injection of iridium and sulfur in the upper mantle was atmost a marginal one.

In the next section we enter carefully the very serious and competitive world of the search for interstellar dust (IS-dust) in extraterrestrial material. Indeed, we felt somewhat obliged to outline this important area of research in this book, even though all our attempts to participate in it have piteously failed –except possibly the first ones in 1975. We discuss essentially:

– the stunning “blitzkrieg” of Yada and Staderman in stardust research, which allowed the recent discovery of six big fat interstellar dust grains in large AMMs from both the French and the Japanese collections;
– the folkloric story of the development of the very powerful instrument, the NanoSIMS, that revolutioned this hunt for subminon size IS-dust.

28 Stardust Attacks in Bob Laboratory for Space Sciences

A world of "hot" spots. Until the very recent reports of Yada et al. (2004, 2005) individual tiny interstellar dust grains (stardust) were only sought in meteorites and SMMs. This is a difficult study, which is based on the search for isotopic anomalies in tiny submicron-sized grains with ion analyzers. They first included graphite, nanodiamonds, silicon carbides, silicon nitride and three varieties of refractory oxide grains, corundum, hibonite and spinel (Zinner, 2004). Since 2003, interstellar silicates were also found in both SMMs (Messenger et al., 2003) and meteorites (Nagashima et al., 2004; Nguyen and Zinner, 2004). A general characteristic of these IS-silicates is that they are quite rare in SMMs (i.e., 0.6% of the silicates), and their abundance is even 10–100 times smaller in meteorites. Furthermore, they have very small sizes (0.01 μm to 1 μm), in good agreement with the expectations of astrophysicists, who worry about their condensation in stellar environments, explosive or not. We recall that the major objectives of this stardust search are to find new constraints for the nucleosynthesis of elements in various stellar environments, the formation of interstellar dust grains and the evolution of the galaxy over the last few Gyr.

Today, this research mostly focuses on a hunt for micron-size "hot spots" showing marked isotopic anomalies within a given larger extraterrestrial dust grain. For example, with the ion imaging device of the NanoSIMS, a large positive anomaly in the heavier isotopes of oxygen will appear as a fantastically mysterious yellow-red hot spot –see the impressive picture reported by Alexander et al. (2005); their Fig. 3. This search is such a difficult endeavour that the discovery of a new single hot spot (that corresponds to anomalies never observed before) warrants a publication in a prestigious journal. One can start worrying about the number of NanoSims that seems to grow exponentially with times and the availability of about 70,000 meteorites in the world collection of meteorites. Consequently these journals might be soon dangerously flooded by hot spots.

Political selection biases. As soon as we found micrometeorites in Greenland cryoconite, we had to choose the best strategy to use them to participate in this game. The Washington University group (in St. Louis) was far ahead of the world competition. So, the best alternative was to collaborate with them to investigate the new large unmelted micrometeorites never collected

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before, and called "giant" by Brownlee. Robert (Bob Walker), the director of the group, warmly welcome us to do so (see below).

However, NASA mobilizes part of the time two stratospheric aircrafts and their crews for a costly recovery of SMMs. Therefore, the top priority for our colleagues supported by US agencies is to exploit these collections. If the first hunt for stardust in AMMs was not successful quickly (this was the case), then they have to quit for SMMs, lunar samples and meteorite studies –these agencies also fund the study of meteorites, in particular because the collections contain rocks coming from the Moon and possibly from Mars, which help prepare the space missions to Mars.

The conjunction between our strategy and this priority funding of SMM and meteorite studies in the US created a kind of political bias in the selection of samples for the search of IS-dust that lasted for about 15 years. Indeed, most colleagues, who did not see any evidence of AMMs in the list of the investigated samples, concluded that they were not worth investigating. This view was probably shared by the reviewers of the proposals of our US colleagues, and this led to a long-lasting noxious selection bias. Even Suzan Taylor and James Lever, who initiated the first collection of US Antarctic micrometeorites at the South Pole station, have had much trouble getting funded for both collecting and analyzing them!

The difficult birth of the NanoSIMS. On our side, we only worried too late about the complex operations required to get a performing ion microprobe and qualified people to run it. We have no excuses. The NanoSIMS is a particularly good case study.

Our laboratory is located on the campus where Slodzian is currently working. In 1980 he proposed the NanoSIMS concept but he could not find the manpower to build the instrument on campus. He left University for ONERA where well trained engineers were available at that time. The first prototype was built at ONERA (Slodzian et al., 1987, 1990) and a few years later a second version whose design was close to the actual instrument (Slodzian et al. 1991, 1992; Hillion et al. 1991). The work was going well at ONERA but after the fall of the Berlin wall the funding for fundamental research was severely cut at ONERA by the Ministry of Defense since there was no threat from the East anymore. The prototype was then "lent" to the French company CAMECA, who went on improving the instrument and preparing its launch on the market with a fabulous war (game) name: NanoSIMS.

I visited ONERA in the 1990s and saw an incredibly sharp picture of industrial micron-sized diamonds obtained with the secondary C^- ions of the NanoSIMS. I was also quite impressed by a composite ion picture of a polished section of a material developed at ONERA and made of SiC fibers embedded into a metallic alloy of titanium (Fig. 50). One of the micrographs is obtained by multiplying the intensity of the C and Si signals, and this procedure considerably enhances the contrast of the SiC-rich zones. Stardust made of SiC particles should thus be easily spotted.

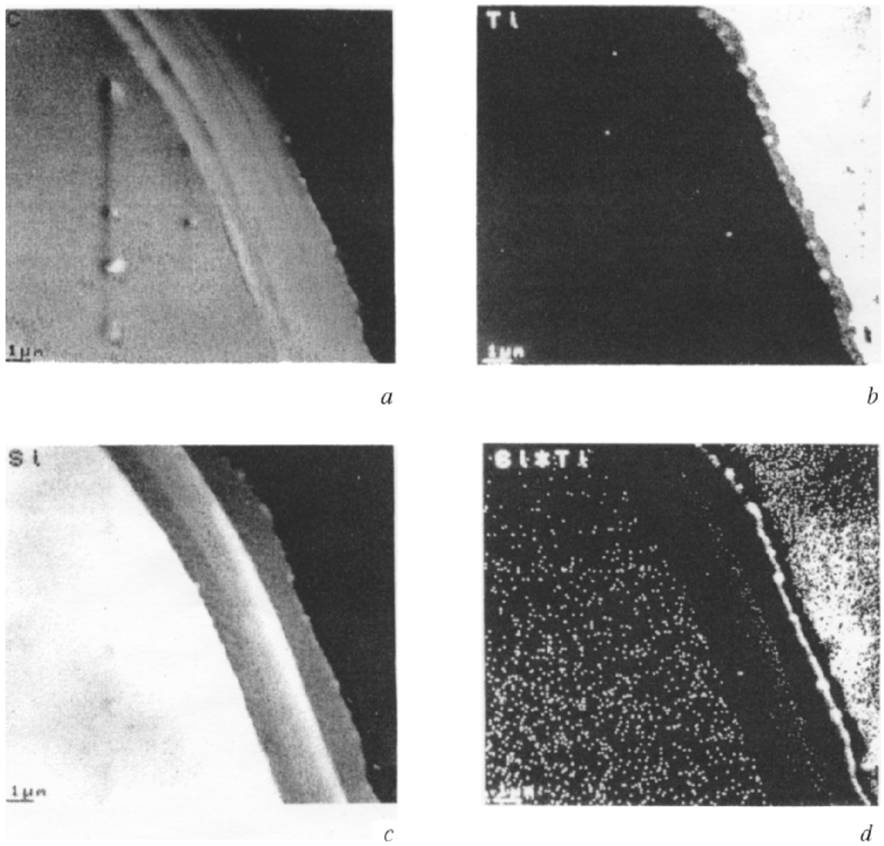

Fig. 50. Secondary ion pictures of the polished section of a composite material made of SiC fibers (diameter of about 50 μm) embedded in a metallic alloy (90% Ti, 6% Al, 4% V). They were obtained in 1991 with the prototype of the NanoSIMS developed at ONERA (size of the field of view 15 μm). The four pictures were acquired simultaneously. They refer from the upper left to the bottom right to carbon, titanium, silicon and to the "hot" spots of Ti and Si obtained by multiplying the peak intensities of these two elements on a given spot, respectively. One can see very clearly the formation of a thin submicron-size rim of Ti on the external surface of the fibers that modifies their properties. The electron micrograph of the same spot with the secondary electrons ejected by the ions is also acquired. This powerful instrument could have already been used in 1991 to detect interstellar SiC grains in the acid resistant residue of Orgueil prepared by Peter Eberhardt in 1974 (Courtesy of G. Slodzian).

I expressed to François Hillion my interest to run the acid-resistant residue that I got from Peter Eberhardt in 1975 to look for diamond and/or SiC stardust in it (see below). Hillion told me that the machine was going to be disassembled. It could not be moved to the Orsay campus because "*no room* *and no means were available*" there to host it! He kindly offered to run a few samples when the machine was be reassembled at the CAMECA plant. But I never found the sample of Eberhardt and hesitated about asking for new ones.

I forgot about this project except to describe to Bob the incredible beauty of the micron-sized diamonds and convey my feeling that this instrument should be the most powerful one to detect stardust. He then started to move fast with his unique blend of perseverance and enthusiasm. He got the funding to buy the first instrument built by the company, after requiring a few changes, i.e., the replacement of the magnet by a larger model to extend the mass range of the instrument. It should be noted that the instrument has been purposely designed to accommodate any special requests of the users that are specific to their own research –i.e., biologists do not want the same magnet and/or the same program of exploitation of the data as astrophysicists. The paradox is that Slodzian could not find again a favorable environment to work on the NanoSIMs or to gain access to the instrument on a long time schedule.

As soon as the instrument was installed at Washington University (c.f., epilogue) the team quickly discovered new stardust grains (see below). I claim (again in the greatest loneliness) that the US victory in the first part of the stardust war (game) is due first to the talent of a Frenchman, who conceived the instrument at the first place, the talent of the US team and its charismatic leader, but also for a major part, to the specificities of the odd French socio-political scientific system.

Earlier works on "Track-Crystallites". While writing this section, I remembered that in 1975 we were probably the first group to search for individual stardust grains in various mineral separates extracted from carbonaceous chondrites, in particular those showing oxygen and neon isotope anomalies (Audouze et al. 1975 and 1976). One of these residues was prepared by Peter Eberhardt, who found large isotopic anomalies of neon defining a Ne–E component, which was supposed to be trapped in a rare stardust component of the meteorite (Eberhardt, 1974).

But the earlier microprobes were hardly available and their spatial resolution was not sufficient to look at the expected submicron-sized grains. We only had access to a high voltage transmission electron microscope (HVEM), which was not equipped at this time with an X-ray system of chemical analysis.

We applied our early "TC-decorating" method to search for heavily irradiated grains in these residues. Latent nuclear particle tracks (produced by iron group nuclei) can be transformed upon vacuum thermal-annealing into tiny track-crystallites (TCs), which can be best observed with the HVEM. As the TCs are very stable in the electron beam of the HVEM, they are particularly useful to decorate either "fresh" latent tracks that fade away very quickly by beam ionization annealing in the microscope, or "fossil" tracks, which are already too weakly contrasted (as a result of their partial thermal annealing in nature) to be directly observed with the HVEM. Moreover, as the sizes of the TCs markedly increase with the annealing temperature, the observation of fossil TCs give some hints about the thermal history of the grains.

We thus observed high density of TCs after a relatively modest heating at 500°C of completely amorphous μm-sized grains of the Ne-E separate of Orgueil and Leoville –see a beautiful picture of these TCs in the figure reported by Audouze et al. (1976). This temperature was known to induce TCs in lunar silicates loaded with tracks. These TCs would thus be indicative of the exposure of these amorphous grains in a high fluence ($\geq 10^{17}$p/cm^2) of low energy ($\sim$10 MeV) protons, which also carried the track producing iron-group nuclei –this fluence was directly deduced from the density of the TCs. Surprisingly, the nuclear interactions induced by this fluence of protons on ^{25}Mg could have simultaneously produced the right excess of Ne-E observed in the residues!

As the fluence of SEP protons bombarding micrometeorites in the interplanetary medium are several orders of magnitude smaller, they could not generate these high TC densities. So, we first suggested that these grains were probably irradiated by interstellar shock waves, thus being stardust particles –but we also cautioned that this irradiation could have occurred during the early T-Tauri phase of the Sun. This irradiation scheme, as deciphered from TEM studies, has been rejuvenated very recently by Westphal and Bradley (2004) to explain the formation of their beautiful amorphous GEMS particles that they found in SMMs.

Then, a few years later in the late 1970s, US groups started to heavily invest in the search for individual stardust in such etching residues. With their improved instrumentation they found the long sought SiC star dust looking in particular at C, Si and N isotopic anomalies (SiC grains contain up to several wt% of nitrogen) –c.f., the review of Hoppe and Ott (1996).

An enviable record of failed attempts. About 10 years after this first unsuccessful attempt, we felt totally confident about making our first brillant attempt to find stardust in our new collections of Greenland and Cap-Prudhomme micrometeorites. Bob welcomed us in his laboratory. They were hoping to discover new types of interstellar dust grains in our new collection of giant micrometeorites coming from the cold.

We extracted upon desegregation of about 1 kg of Greenland cryoconite (on a 100 mesh stainless steel sieve) about 6 g of glacial sand with a size ≥100 μm. This sand was subjected to a complex protocol of etching that removed most of the stony and organic material, thus hopefully enriching this "acid-resistant" residue in interstellar SiC. The search was unsuccessful (Prombo et al., 1991). About 100 SiC grains were discovered, but all of them were terrestrial as indicated by the isotopic composition of their minor component of nitrogen.

A few years later, I realized that the room where I desegregated cryoconite was dedicated to polishing, and SiC was used in one of the major polishing steps. So, we had a least an interpretation for the dominance of terrestrial SiC grains in the etching residue, which was a puzzle for some time. We even wondered whether or not there was a production plant for SiC powder in the northern hemisphere that could feed the winds reaching Greenland and the west melt zone of its ice sheet. Bob with his great enthusiasm succeeded in convincing me that the major suspect was . . . the US!

A second attempt was made in the same laboratory during the course of a successful study of the neon isotopic composition of Antarctic micrometeorites (Maurette et al., 1991a). In this earlier study, each one of the seven AMMs selected for this study was mounted in epoxy plugs, then polished and examined with an analytical scanning electron microscope to characterize their chondritic and mineralogical compositions. They were then extracted from the mount and split into several pieces. One of them was volatilized with a laser to investigate its neon isotopic composition with an ultra-sensitive noble gas mass spectrometer. Another one was crushed on a gold foil and investigated by Stadermann and Olinger (1992) with an earlier ion analyzer model (IMF-3f), which was conceived by Slodzian in 1962 (Castaing and Slodzian, 1962).

At that time, they did not think about finding individual IS-grains. They were just looking for bulk isotopic anomalies that were already found in SMMs (i.e., high D/H and $^{14}N/^{15}N$ ratios), and which would have been indicative of a component of organics synthesized by cold molecular cloud chemistry. This search was also unsuccessful. Moreover, Yates (1993) and Strebel et al. (1998) searched unsuccessfully for stardust in cryoconite samples from Greenland. This was the end for the search for IS-grains in AMMs. Our colleagues had to return to the business of SMMs and meteorites, which were looking much more promising to all of them.

Since 1998, I have been frequently ruminating in the discreet loneliness of defeat. It was evident that if interstellar refractory oxides and SiC grains did exist in both the tiny 10–20 μm size SMMs and the approximately 100 kg total mass of the various fragments of Murchison recovered in Australia, they should also exist in AMMs with intermediate sizes of 50–200 μm! Indeed, these minerals are among the most stable against both cryogenic weathering and frictional heating upon atmospheric entry.

The stunning "blitz krieg" of Yada and Stadermann. In brief, until May 2004, a biased search for stardust was only conducted on SMMs and meteorites. This hunt has been revolutionized by the availability of the NanoSIMS. With this instrument, submicron-sized interstellar silicates (also called presolar) are recognized by their higher abundance of ^{17}O relative to those of the stable isotopes ^{16}O and ^{18}O than do solar system materials. Messenger et al. (2003) ran 1031 anhydrous silicates with very small sizes (0.3–0.9 μm) in SMMs. Six of them turned out to be stardust.

About two year ago, Slodzian joined our group with a latter version (4f) of the old IMF-3f. He made a lot of modifications to improve isotopic measurement reproducibility. The performance of this instrument cannot compare to those of the NanoSIMS. However, we though that they were good enough to make a more successful intrusion in *stardust mania* than in the past. Alas! What looked like a "simple" quiet French project in the routine analysis of hundreds AMMs was shattered when Frank Stadermann kindly asked me in June 2004 to be a co-author on a paper in preparation (I declined this kind offer).

Stunningly, this paper deals with the Cap-Prudhomme AMMs, which were ignored for about 15 years. What incredible timing for a collision of our two projects. Again they were the winners, and I could understand the feelings of Napoleon at Waterloo when the English and the Prussians defeated him on June 1815!

Yada et al. (2004a) investigated with the NanoSIMS the fragments of AMMs crushed onto a gold foil, which were already run without success in the early 1990s (Stadermann and Olinger, 1992). They found a kind of giant interstellar silicate grain with a cross section of about 5μm × 3μm and a huge enrichment in ^{17}O that proves its interstellar origin (δ^{17}O = +2700 in the per mil notation of geochemists), which corresponds to a ^{17}O/^{16}O ratio about 3.7 times higher than the reference terrestrial value –also inferred from an average of the terrestrial oceans like the standard SMOW value of the D/H ratio. Then six other Antarctic micrometeorites selected in the Japanese collections were analysed the same way (Yada et al., 2005), and 5 additional stardust grains showing a typical large excess of ^{17}O were found.

A total of about 37000 μm^2 surface area of the pressed surfaces of the 13 AMMs was analyzed in about 86 ion imaging runs each lasting more than six hours! All these grains are related to silicates. This can be translated in terms of a concentration of interstellar silicates of 300 ppm, which is comparable to that ($\sim$400 ppm) found in the specific selection of the porous anhydrous SMMs. Both concentrations are thus about 10 times higher than those found in carbonaceous chondrites of about 30 ppm –c.f., Nagashima et al., 2004; Nguyen and Zinner 2004. Notably, the size of these silicate stardust particles in AMMs are much larger than those observed in meteorites (0.1–1 μm) and SMMs (0.3–0.9 μm).

This should have ended the folklore of the soft unsuccessful French attacks in *stardust mania*. But we noted that the discovery of each interstellar dust particle needed about one week of automated ion imaging hunting with the NanoSIMS. We can scan much faster (with the rejuvinated old ancestor IMF-3f) the surface of hundreds of AMMs to look for the most promising particles showing some micron-sized "hot" spot greatly enriched in ^{17}O. Then, these particles could be subsequently run at Washington University. However, Bob, with his explosive enthusiasm that always made things more exciting is no longer with us. This is so sad.

29 Challenges Still to Be Appropriately Addressed

This section includes a heteroclite set of questions and comments of colleagues, which have still to be fully answered. Progress in science occurs not only with a few spectacular achievements that are generally cleverly advertised by funding agencies and the prestigious journals, but also by incessant questioning. They remain in the shadow for a while because you have to wait for an answer that might never come.

29.1 The Opaque Mystery of the Heavy Noble Gases

A large excess of ^{36}Ar and ^{84}Kr in the Earth's atmosphere. The accretion formula accounts rather well for the total amount of neon in the atmosphere and its predicted early solar isotopic composition, which is still found in rocks from the upper mantle. In contrast, with the concentrations of the heavy noble gases measured in Japanese Antarctic micrometeorites, the accretion formula leads to total amounts of micrometeoritic ^{36}Ar and ^{84}Kr in the atmosphere which are about 20 and 200 times smaller than the observed quantities, respectively.

The missing Xe. Moreover, the ratios of ^{132}Xe/^{32}Ar and ^{132}Xe/^{84}Kr in the atmosphere are about 10 times lower than in the "planetary component" of carbonaceous chondrites and AMMs. This depletion constitutes the mystery of the "missing" xenon. Astonishingly, the accretion formula predicts a total amount of micrometeoritic ^{132}Xe that is only 3 times smaller than the atmospheric value. This difference looks insignificant when considering the very long extrapolation of EMMA back in time and the huge misfits with Ar and Kr. However, the isotopic compositions of atmospheric and micrometeoritic xenon are markedly different.

This deduction was made about 15 years ago by Sarda et al. (1991), who made for the first time a complete noble gas study (by stepped heating) of a 400 µm fragment, extracted from a very large ∼800 µm unmelted micrometeorite recovered from Greenland (Fig. 51). The isotopic composition of micrometeoritic xenon is similar to that of "planetary" xenon found in CM-type chondrites, such as Murray (Fig. 52) –Osawa et al. (2000, 2002) reconfirmed recently this finding for AMMs. However, it is very different from

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DOI: 10.1007/10911310_29

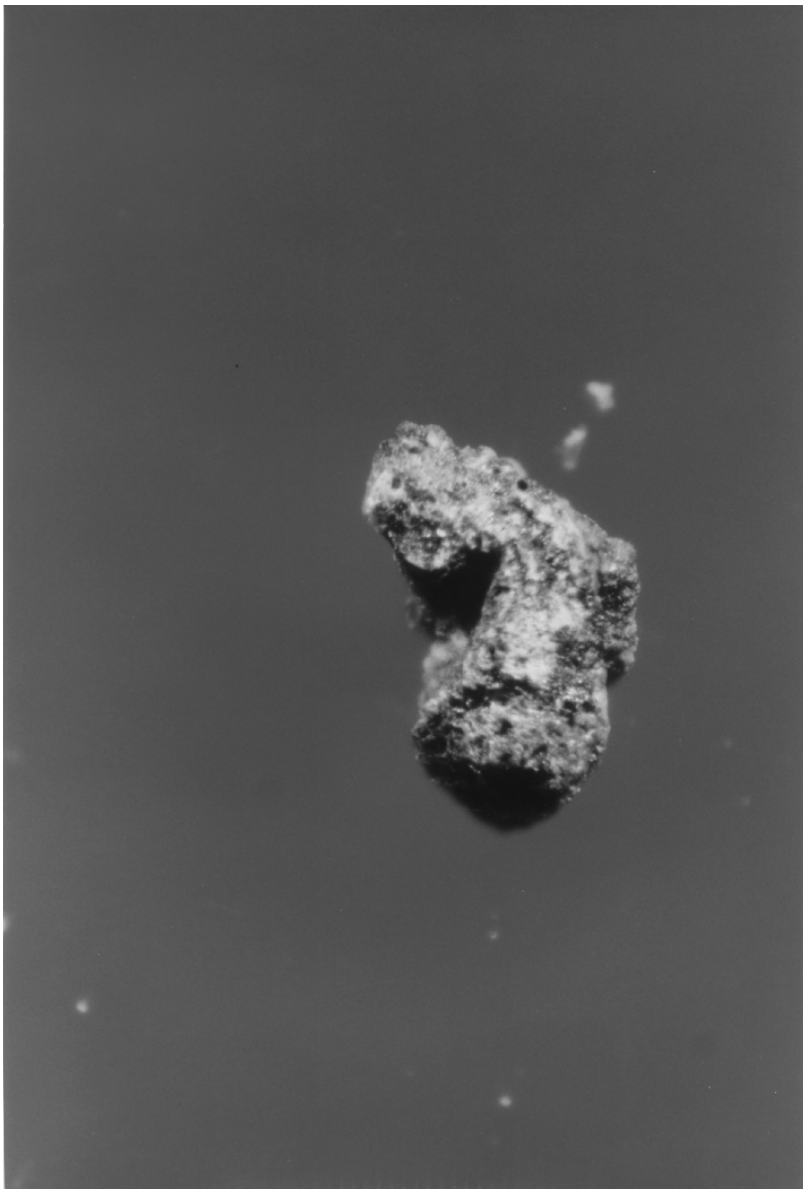

Fig. 51. This unmelted fine-grained micrometeorite with a size of about 800 µm was collected during the Blue Lake II expedition in Greenland (June 1992). It was found in the ≥400 µm size fraction of the glacial sand extracted from cryoconite. The cavity observed on the left hand side decorates the extraction of an approximately 230 µg chunk of micrometeorite, which was analyzed by Sarda et al. (1993).

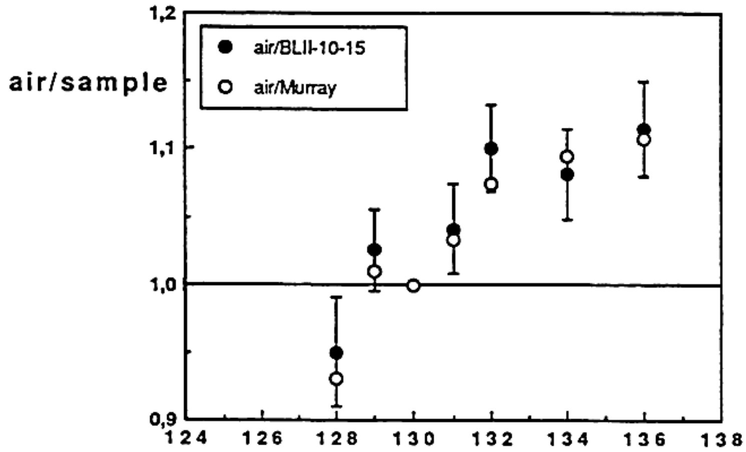

Fig. 52. The isotopic compositions of xenon in the approximately 400 μm-sized fragment of the large Greenland micrometeorite and in a CM2-type chondrite (Murray) are expressed relative to that measured in the air. The micrometeorite composition, which strikingly mimics the planetary composition of Murray, is very different from that of the air (Courtesy of Ph. Sarda).

that observed in the Earth's atmosphere, which shows a strong depletion of the light xenon isotopes. These observations further confirm the close relationship between the constituent material of AMMs and CM-type chondrites –see Sect. 25. They also contribute to further deepen the opaque mystery of the provenance of the heavy noble gases in the atmosphere.

29.2 Japanese Doubts about the Physics of the Giant Moon-forming Impact

The Moon-forming impact did produce enormous mechanical and thermal effects. Among the theoreticians, who describe these effects, the situations is quite confusing. Ahrens and collaborators in their earlier works described the degree of "mechanical" atmospheric erosion due to the global ground motion excited by the strong shock wave of the impact traveling in the planetary interior. They concluded that this process is sufficient to "virtually" launch almost all particles of the atmosphere to escape velocity, by direct ejection of the impacted hemisphere and by shock-induced outward ramming of the antipodal planetary surface.

Recently, Abe et al. (2002) and Genda and Abe (2003) challenged the physics involved in the model of Ahrens (1993). Accordingly to the new model, only a minor fraction (∼20%) of the atmosphere will be blown off during such an impact. Moreover, during the growth of the young Earth, about

50% of the atmosphere of each of the most massive planetary embryos (i.e., with masses in excess of about 4 lunar masses) would also be retained, thus getting mixed into the growing Earth's atmosphere. As already pointed out in Sect. 4.2, the final composition of the atmosphere would be very complex. This model is thus inadequate because it stumbles against the micrometeorite purity of the atmosphere, which requires that at least 90% of the pre-impact atmosphere should have been lost to space.

In an improved version of the earlier model of Ahrens, Shen et al. (2003) noted "ground motion alone is not sufficient to propel the full Earth atmosphere. However, this process is one of the many propelling processes which can significantly accelerate atmosphere to escape the Earth's gravity field" –see reference herein as well as the works of Benz and Cameron (1990) and Pepin (1991) about the thermal effects of this impact, which could lead to a massive hydrodynamic escape of the upper atmosphere.

Surprisingly, with an improved version of their model, Genda and Abee (2005) now conclude that "the presence of an ocean significantly enhances the loss of atmosphere during a giant impact". Both groups might now consider the new experimental constraint of the micrometeoritic purity of the atmosphere, which implies that the pre-lunar atmosphere was blow off during the formation of the Moon.

29.3 The New Hf-W Chronology Invalidates the Timing of EMMA?

With the fast development of the MC–ICP–MS technique (multiple-collector inductively-coupled plasma mass spectrometry), which allows extending isotopic measurements to almost all elements of the periodic table, the number of new radioametric chronometers has drastically increased over the last few years (Albarède, 2002). It is still difficult to understand the meaning of the "model" dependent ages inferred from such chronometers. The most careful specialists strongly recommend conducting simultaneous petrographic studies of the rocks for a more reliable exploitation of these chronometers.

Regarding the major early solar system events considered by EMMA, one of the new chronometers (^{182}Hf–^{182}W) yields much shorter ages of formation for both the Earth and the Moon of about 34 Ma (Schoenberg et al., 2002). This chronology is not in agreement either with the noble gas chronology or the predictions of planetary dynamicists that the period of merging of planetary embryo with the proto-Earth extended to about 100–200 Myr. In this chronology, big bodies were still bombarding the Earth after the formation of the Moon, thus spoiling the micrometeoritic purity of the early atmosphere with their volatiles.

Certainly, the Hf–W system dates a major episode of fractionation involving the fusion of rocks and a segregation of iron where W ended up being captured. However, the date of this segregation might just give the age of differentiation of the planetary embryos (c.f., Sect. 3.2). Indeed, the Moon and Mars, which somewhat bracket the range of values postulated for the masses of these embryos (about 1 to 10 lunar masses) both have a metallic core. In this case the Hf–W chronometer would just give the average time of formation of the embryo metallic cores and not the chronology of their subsequent accretion into a planet, which was effective over a longer time scale of about 100 Myr.

29.4 The Need for a Strong EUV Heating of the Early Thermosphere Invalidates EMMA?

Conventional views about the requirement of a strong solar EUV heating of the early thermosphere. A reviewer of one of our papers argued, "the timing of EMMA is wrong". In conventional theories, the preferential gravitational escape of ^{20}Ne that decreases the ^{20}Ne/^{22}Ne ratio to the atmospheric value is produced by the gravitational escape of a huge flux of H_2 resulting from the breakdown of water molecules –either by photodissociation in the atmosphere or by reduction of water in the interior followed by degassing.

The argument is that this "hydrodynamical" escape requires not only the dissociation of water molecules to produce the required flux of H_2, but also a strongly focused heating of the upper thermosphere to sufficiently increase the speed of the escaping H_2. Therefore, since the pioneering and concise work of Hunten et al. (1987), colleagues invoke the heating of the thermosphere by the enhanced flux of EUV radiation of the young Sun, which is readily absorbed in the upper thermosphere. Some of them try to extend this period beyond 100 Myr. However, the EUV emission of a young Sun-like star is correlated with its X-ray emission, which is related to its magnetic activity that decays quickly in about 20 Myr (Zahnle and Walker, 1982).

Thus, at the end of the formation time interval of the Earth, $\Delta(Earth)$ $\sim$100 Myr, a young Sun-type star can hardly provide this amount of EUV radiation. In the logic of the reviewer, the fractionation of neon would have been necessarily produced before the end of $\Delta(Earth)$. Therefore, the right ^{20}Ne/^{22}Ne atmospheric ratio of the present day atmosphere involved prelunar neon, and not the post-lunar neon, which according to EMMA was delivered by juvenile micrometeorites!

Frictional heating of air molecules during the deceleration of micrometeorites. We got stuck for about a year with this deadly criticism. While trying anxiously to find a flaw in this reasoning, we suddenly remembered the frictional heating of the leading edge of micrometeorite upon atmospheric entry (Sect. 17.2).

During the "peak" of the LHBomb (e.g., the period of about 100 Myr that followed the formation of the Moon) the kinetic energy lost by juvenile micrometeorites during their sharp deceleration in the atmosphere was about 130 and 6400 ergs/cm^2/s for the minimum and maximum speeds of the incoming micrometeorites, of about 10 and 70 km/sec, respectively. For the average speed of about 15 km/sec inferred from the distribution of the speeds of radar meteors (Fraundorf, 1980), one thus gets a value of 250 ergs/cm/sec, which is higher than the value inferred for the enhanced EUV emission of the young Sun!

Even more surprising, this energy release was confined just to the right zone delineated by the deceleration range of micrometeorites in the upper thermosphere, where the process of hydrodynamic escape is the most efficient. This focalised delivery of micrometeoritic energy is sufficient to induce a long duration heating of the thermosphere, which lasted about 100 Myr after the formation of the Moon. One thus gets rid of the severe constraint of driving the gravitational escape of ^{20}Ne through the assistance of the enhanced EUV flux of the young Sun (see Sect. 17.2). Moreover, the process of hydrodynamical escape should have been particularly efficient in this zone, where water and Ne were simultaneously delivered! There was no need anymore to inject water and neon from lower layers of the atmosphere or from the Earth's interior, which always poses problems.

29.5 Light or Heavy Micrometeorite SMOW Water

A terrestrial water contamination of micrometeorites? One of the backbones of our scenario is the astonishing similarity between the average micrometeoritic D/H ratio and the SMOW value of terrestrial water. As soon as our first paper was published an immediate criticism was that the SMOW water found in micrometeorites just reflects their contamination by the SMOW terrestrial water.

In this context, the contamination should have only occurred through isotopic exchange between the hydrous silicates of AMMs and Antarctic melt ice water, produced during either cryogenic weathering while the grains resided in the first top meter of the blue ice field (c.f. Sect. 5.4) or during their exposure for about 8 hours in their host pockets of melted ice at temperatures of a few °C. This last exposure in cold water was too short to induce detectable change. However, cryogenic weathering was effective over the period of about 20 years between the times when the blue ice emerged upward from the top snow layer at a few kilometers from margin and then moved to the collection site near the sea shore –before, the ice was shielded by a thick snowbank that shut down cryogenic weathering. Some colleagues even insisted that when the crystalline structure of hydrous-silicates has not been completely destroyed upon heating, then they can quickly re-hydrate when they are immersed in water.

Fortunately, Antarctic melted ice water shows the lowest D/H ratio observed on the Earth, about 1.5 times smaller than SMOW. Consequently, it is hard to believe that this peculiar weathering, effective over a period of 20 years, only during the short Antarctic summer, would have miraculously decreased an initially high D/H ratio locked in micrometeorites to just fit the SMOW value!

This deduction is further supported by the ion microprobe analysis of a variety of cosmic spherules from the Cap-Prudhomme collection, called chondritic-barred spherules, which are among the most abundant ones. These spherules are made of bars of olivine separated by thin interstitial lamella of glass (see Fig. 31). In spherules magnetically extracted from deep sea sediments or scooped on the surface of Antarctic blue ice fields in the Transantarctic mountains (Koeberl and Hagen, 1989; Harvey and Maurette, 1991), the glass lamella have been preferentially corroded thus leaving a typical pattern of long tiny etch canals that can penetrate up to the centre of the spherules. In contrast, the etch canals of spherules from Cap-Prudhomme were not formed at depths $\geq 1\,\mu$m

Ion microprobe analysis of the intact cores of the spherules show that a few of them still contain a measurable amount of water, ranging from about 0.1 to 1.2%, which was not completely degased out gassed during the fast quenching of the melted parent droplets of the spherules upon atmospheric entry. The D/H ratio of this water is similar to that observed for unmelted AMMs. We thus consider that this specific problem has now been fully addressed.

A real deficit of micrometeoritic water? We still do not know whether the deficit of water predicted by EMMA (i.e., by a factor 2–3) is significant or not. Pepin (1991) concluded that about 50% of the water molecules initially injected in the atmosphere has to be broken down to feed the flux of escaping H_2 required in the model of Ozima and Zahnle (1993) to trigger the preferential escape of ^{20}Ne, in order to decrease the initial solar wind ^{20}Ne/^{22}Ne ratio ($\sim$13.8) to the atmospheric value of about 9.8. If such a water loss was indeed effective, then the initial amount of SMOW water on the early Earth should have been about 2 times higher. Therefore, the deficit of water predicted by EMMA would get sufficiently larger (about a factor 4–6) to become significant.

All these earlier works considered the high solar ratio ($\sim$13.8) observed in the solar wind. Thus, a large amount of dissociated water is necessary to reach the present-day final ratio of about 9.8. But in EMMA this initial ratio would now corresponds to the smaller average value measured in AMMs ($\sim$11.8). Minoru Ozima kindly calculated for us that the quantity of dissociated water necessary to decrease the micrometeoritic value to the atmospheric value is at most 10–20%. As already pointed out in the previous section, micrometeorites delivered themselves in the same layer of the thermosphere both the water molecules to feed hydrodynamical escape and the required amount of energy to increase the speed of H_2. It seems that the conjunction of these processes, which were astonishingly well tuned in both space and time, further decreased the amount of water required to drive this process.

Micrometeorite SMOW water cannot yield the SMOW oceans! In brief the argument underlying this criticism looks at first glance so sound that it helped to reject one of our papers. The dissociation of water molecules triggered a preferential gravitational escape of H_2 with regard to D_2, which is twice as massive. This effect progressively enriched the residual atmosphere in deuterium, thus shifting the D/H ratio to a higher value. Therefore, the micrometeoritic SMOW water should have ended up yielding a water enriched in deuterium, like on Mars and Venus.

In fact the Earth is an exception, being the only planet that does not show a noticeable shift of the SMOW value relative to the micrometeoritic value, while Mars and Venus show a huge fractionation of this D/H ratio. The dissociation of water starts forming H and D ions that quickly end up forming H_2 and D_2 but also DH. As each deuterium atom is surrounded by 10^4 times more hydrogen atoms, the DH molecules could have been much more abundant than D_2. Furthermore, if the thermosphere was simultaneously heated up at much higher temperatures, then the loss of H_2 and DH should have been rather comparable. Thus the D/H ratio of the residual micrometeorite water would have been only slightly fractionated. Moreover, the fraction of water that has to be discomposed in order to generate the H_2 flux that drives the preferential hydrodynamic escape of ^{20}Ne was smaller than previously thought due to the lower initial $^{20}Ne/^{22}Ne$ ratio delivered to the Earth by juvenile micrometeorites (see Sect. 19.3).

It is likely that the combination of these effects markedly decreased the amount of water required to drive hydrodynamical escape. This contributed to limit the excess of deuterium on the Earth. But why is it that this process was not efficient on Mars and Venus, which show D/H ratios about 4 times and at least 10 times higher, respectively, than the SMOW value?

In fact, this problem should be even worse in the last version of the GwetA model, presented by Morbidelli et al. (2000), and attributing the formation of the atmosphere to the impact of a CI- type giant *wet* asteroid. Indeed, the initial D/H ratio of their constituent water is already higher than the SMOW value (see Fig. 22). Soon after being hit by this additional deadly criticism, we got more relaxed while noting that the list of the co-authors of this paper include experts about the origin of water in the solar system. They were certainly also disregarding this criticism for good reasons.

Light or heavy micrometeorite SMOW water? Matrajt et al. (2005) reported a noticeable enrichment of the heaviest isotopes of oxygen (^{17}O and ^{18}O) in all types of micrometeorites from the South Pole collection. This fractionation is conveniently displayed on a linear plot, which relates the oxygen isotope abundances, $\delta^{17}O$ and $\delta^{18}O$ expressed with units of "per mil" –for example $\delta^{17}O = [(^{17}O/^{16}O)_1/(^{17}O/^{16}O)_0 - 1] \times 1000$; in this expression, the subscript 1 and 0 refer to the sample and the reference sample, respectively. Curiously, the reference sample is the oxygen of the SMOW water of the oceans (i.e., micrometeorite water?). They argued that this variation indicate that the oxygen of micrometeorites is different from the chondritic value. Therefore, micrometeorites would represent a new class of solar system bodies.

But critics were quick to spot the rare variety of "I-type" spherules, made of a mixture of iron oxides (magnetite and wüstite), and which give the highest (i.e., "marked") enrichments. These spherules were mostly recovered by magnetic raking from deep sea sediments. Their enrichments in the heavy isotopes of oxygen and iron were found to be correlated. This was interpreted by a process of fractionated distillation during atmospheric entry –see Taylor et al. (2005) for a review of previous works. Therefore, the clustering of fine-grained and scoriaceous AMMs on the same oxygen fractionation line than the spherules (but in the lower range of "noticeable" enrichments) would imply that they lost their light oxygen isotopes by the same process of fractionated distillation.

In the logic of this critic, the lightest of all isotopes, hydrogen, would have been severely lost relatively to deuterium. Consequently, micrometeorites that are collected on the Earth's surface would be enriched in heavy water relatively to their pre-atmospheric water. But oddly enough, this residual heavy water has the.... SMOW composition ($\delta^2\mathrm{H} = 0$)! Consequently, the initial constituent water of micrometeorite was anomalously light (i.e., with a negative δ^2H) as to rightly yields the residual heavier SMOW water locked in them.

In brief, the various criticisms briefly outlined in this section propose that the SMOW water of the oceans cannot be the SMOW water locked in micrometeorites. Depending on the critic, the initial composition of micrometeorite water would thus be either markedly lighter or markedly heavier than SMOW. So, as Pierre Dac refused to help us while facing this distressing dilemma of choosing the right answer, we decided courageously to select the most probable "median" value, SMOW!

29.6 Nitrogen on Trial

A bizarre drop in nitrogen content. Nitrogen is one of the most important volatiles in our scenario. It defines the $Ne/N_2, H_2O/N_2$ and CO_2/N_2 ratios, which characterize the micrometeoritic purity of the Earth's atmosphere. It was also a key biogenic element in the prebiotic chemistry of life. Moreover, the nitrogen content of the atmosphere and AMMs combine as to give a precious estimate of the total mass influx of micrometeorites, $\Phi(t_1)$, without worrying about the LHBomb. The remarkable agreement between this "nitrogen" flux and two other independent influx estimates inferred from neon and lunar cratering rates (see Sects. 10.3 and 10.4) somewhat validates indirectly the average N contents of AMMs reported by Matrajt et al. (2003).

They checked first the reliability of the nuclear microprobe technique used to measure both the C and N contents of AMMs (see Sect. 9.1) while determining the contents of these two elements in two hydrous-carbonaceous chondrites soon collected after their fall, Murchison and Tagish-Lake, which thus suffered a minimum amount of terrestrial weathering and/or contamination. These contents were compared in particular to the values obtained for the same meteorites with the most sensitive and reliable technique of stepped combustion, which was recently improved by Grady et al. (2002). In Murchison and Tagish-Lake the nuclear microprobe yields carbon contents of 2.7–2.8 wt.% and 5.5–6.2 wt.%, respectively, while the stepped combustion of larger amount of meteorite gives 2.22 wt.% and 5.81 wt.%, respectively. The nuclear microprobe shows that the nitrogen content of the two meteorites is about 0.14 wt.% and 0.15–0.22 wt.%, respectively, while stepped combustion indicates concentrations of about 0.097 wt. % and 0.12 wt.%, respectively.

This fit looks quite satisfactory, taking into consideration that all the $\sim$100 µm size fragments analyzed with the nuclear microprobe are heterogeneous on a microscale. However, in a recent paper, Marty et al. (2005) tried to demonstrate the potential of a newly built noble gas mass spectrometer. They thus analyzed an aliquot of AMMs and cosmic spherules that we prepared for them more than 3 years ago. They found very low content of nitrogen of about 4–165 ppm, to be contrasted with the much higher range of values (about 300–900 ppm) reported by Matrajt et al. for micrometeorites extracted from the same aliquots of glacial sand (see Sect. 9.1, second Subsect.). Therefore the analyses of one of the group are necessarily very wrong!

Scrutinizing the counter evidences. We noted several inconsistencies in the results of Marty et al. Let us recall first a few simple features about the classification of micrometeorites on a scale of increasing heating upon atmospheric, which was already used by Clemett et al. (1998). The SEM micrographs reported on Fig. 15 show: fine-grained AMMs (Fg-AMMs); scoriaceous fine-grained AMMs (Sc-AMMs) loaded with vesicles; coarse-grained crystalline AMMs (Xtal-AMMs) made of a few single crystals of olivine and pyroxene, and; thoroughly melted AMMs also called cosmic spherules (CSs). The Fg-AMMs (particles 92-13-28 and 92-13-29) have been less heated up than Sc-AMMs (particle 94-19-8), and both types of AMMs have been much less heated up than CSs (particle 92-23-77).

Moreover, kerogen is the dominant carbonaceous material of hydrous-carbonaceous chondrites, to which 99% of the AMMs are related. This is a very refractory organics, which starts to be degraded around a temperature of $\sim$600°C, when neon starts also to be lost. This is also the major host phase of nitrogen, which is trapped in their fine grained matrix and not in their dry coarse-grained crystalline components, such as olivines, pyroxenes, chondrules and refractory inclusions. Therefore, crystalline micrometeorites that are mostly aggregates of olivines and pyroxenes (see particle 92-8-5), as well as strongly recrystallized Sc-AMMs filled up with tiny crystallites (see

Clemett et al., 1998; their particles 95-3-20 in Fig. 1a), should show very low N content. Moreover, the content of nitrogen should somewhat correlates with that of neon in the fine-grained and scoriaceous type AMMs –crystalline AMMs should be excluded from this search for correlation with neon because they are composed of dry silicates in which Ne is best retained while the content of nitrogen is very low in the crystalline silicates.

None of these trends are observed in the data reported by Marty et al. In particular, the second and third largest N contents of 90 ppm and 87 ppm are observed in a crystalline AMM and a CS, respectively, and the richest AMM (165 ppm of N) is not a fine-grained AMMs but one of the most strongly heated up vesicular Sc-MM. Finally, the N and Ne contents are not correlated. In sharp contrast, all these expected trends are clearly observed in the data set of Matrajt (i.e., beside neon that was not measured in the particles). In particular one of the crystalline AMM (99-11-61) and Fg-AMM (99-11-21) investigated by Marty et al., were also run by Matrajt et al. They found a nitrogen content of about 54 ppm in the crystalline AMM, i.e., a value about 10 times smaller than that measured in the fg-MM ($\sim$477 ppm). The lowest value was very near the background value estimated for a fragment of terrestrial olivine.

These observations give a hint that the blank level (that weights the contamination of the micrometeoritic signal by terrestrial nitrogen) was too high in the analysis of Marty et al. They report that they measured rightly the N content of two samples of Murchison. But these samples of about 200 μg and 270 μg were about 10 times more massive than the fragments of AMMs analyzed in their work, and they could thus yield a signal well above background. In contrast, Matrajt et al. did use fragments of Murchison and Tagish Lake with sizes of about 100 μm quite comparable to those of the AMMs analyzed in their work. In a previous work dealing with the measurement of nitrogen in individual lunar dust grains about 10 times more massive than the AMMs investigated in their work, and which was conducted with an earlier version of this mass spectrometer, huge blank levels were already reported (see Wieler et al., 1999) –they were mainly attributed by the purification procedure.

Marty et al. also concluded that the carbon content of AMMs were also overestimated by Matrajt et al. and they quoted the paper of Wright et al. (1997) to support their claim. This paper only deals with the content and isotopic composition of carbon in seven micrometeorites that were extracted from Greenland cryoconite and four Antarctic micrometeorites. The micrometeorites were gently crushed as to try to get two fragments. With the exception of the smallest Greenland micrometeorite (about 6 μg), which is about 5 times less massive than the other micrometeorite fragments, and which oddly enough yielded a normal carbon content of $\sim$1.5%, all the other values were smaller than about 0.2 wt.%. As rightly noted by Marty et al., they are thus about 10 times smaller than the average carbon content of about 1.6 wt.% deduced by Matrajt et al. for AMMs that are not CS or Xtal-AMM.

However, in the first paragraph of their subsection about "Petrographic Analyses" Wright et al. quote: *the Greenland micrometeorites and 3 AMMs were found to be barred in texture* (this means that they are just crushed barred chondritic cosmic spherules) *and the remaining two AMMs* (therefore one AMM was added somewhere between pages 80 and 81) *had a porphyritic texture*, i.e., they are just scoriaceous particles that got so much heated up that they did fully recrystallize upon cooling! Furthermore, all micrometeorite fragments with the exception of two of the AMMs only exposed to acetone, were washed in dichloromethane, which is one of the most powerful organic solvent. Sure enough, there was not a lot of kerogen fooling around as to yield strong carbon and nitrogen signals! Curiously, an earlier independent measurement of the average carbon content of micrometeorites, which is well compatible with the values estimated by Matrajt et al. (about 2.5%), was made with an ion microprobe technique previously developed for meteorites in the laboratory where the noble gas mass spectrometer of Marty et al. has been built (Engrand and Maurette, 1998).

Other independent testimonies for high contents of kerogen in micrometeorites. Kerogen is characterized by C/N ratios that vary from about 20 to 50. One of the advantages of the nuclear microprobe is that the carbon and nitrogen contents can me measured on a given ~10 µm size spot. The averaging of many spots then yield the average C/N ratio of micrometeorites that well fit the range of values measured in HCCs. It was thus found that the C/N ratios measured with the nuclear microprobe in the best preserved Fg-AMMs (99-11-21 and 99-12-72) are within the range of values measured for Murchison (~23) and Tagish-Lake (~48).

About 15 years ago, we made a straightforward analysis of AMMs with a Fourier-transform IR microscope on zones of 40 µm × 40 µm. It immediately revealed several characteristic absorption bands expected from the building blocks of kerogen between 700 and 1100 cm^{-1} (they are attributed to CH out of plane deformations). The strength of the typical absorption bands indicates a content of refractory organics (i.e., kerogen) of approximately several percents –see micrograph b and c, and the corresponding IR spectra b and c, in Maurette et al. (1990). As expected, the crystalline micrometeorite (micrograph a, and spectra a) did not show PAHs.

Eight year later, the powerful μL^2MS technique (Two-steps laser desorption/laser ionisation Mass Spectrometry), where the second UV laser is specifically tuned as to only ionize the constituent building blocks of kerogen, coined as PAH-moieties (PAHs is the acronym for Polycyclic Aromatic Hydrocarbons), was applied to both two HCCs (Murchison and Orgueil) and one "drier" carbonaceous chondrite, Allende (see Clemett et al., 1998). The total yields of PAHs desorbed by the Fg-AMMs are comparable to that of Murchison –see Fig. 26 and Clemett et al. (1998) for further details. This implies that the kerogen content of micrometeorites is similar to that of Murchison.

The verdict. These very different types of observations show that the content of the major host phase of both carbon and nitrogen (i.e., kerogen) in Fg-AMMs, cannot be 20 times smaller than that measured in Murchison. Therefore, the verdict is that we have still to use the nitrogen contents inferred by Matrajt et al. (i.e., about 300–1000 ppm) and forget about the very low contents of N and/or C reported by the two other groups.

29.7 Further Search for a Micrometeorite Contamination of Mars and Venus

We already had a hard time while assessing the micrometeorite contamination of Ni and S in the Martian soils (Sect. 21.2). The problem looks simpler for volatiles such as Ne, N_2 and CO_2. EMMA predicts that the initial atmospheres of the terrestrial planets should have a rather similar "micrometeoritic" purity (c.f., the cartoon of planetary formation outlined in Sect. 21.2 for Mars) on the condition that the merging of the last planetary embryo did occur at about the same time (i.e., near the end of the formation time interval of the Earth of about 100 Myr). In this case some remnants of this composition should still be found on Venus and Mars. A first hint is given by the Ne/N_2 and CO_2/N_2 ratio observed on the 3 terrestrial planets that are similar within a factor 2–3.

But Venus and Mars are strongly depleted in water. One can hopefully get further clues about the fate of water while considering the present-day $^{20}Ne/^{22}Ne$ ratios measured in the atmosphere of the three planets, relative to the micrometeorite value. The value reported for the Earth and Mars, are quite similar (i.e., about 9.8 and 10.1, respectively; c.f., Owen, 1998). They could derive from micrometeoritic solar neon with an average $^{20}Ne/^{22}Ne$ ratio of 11.8, by a preferential loss of ^{20}Ne induced by the process of hydrodynamical escape fed by the breakup of water molecules, which was shown to work for the Earth. In sharp contrast, the ratio of 11.9 quoted for Venus by Owen (1998) appears to be similar to the micrometeoritic value (i.e., within the error bars of the measurements for Venus). Therefore, it could be deduced that solar neon delivered by early micrometeorites was not fractionated on Venus, while the atmosphere of the Earth and Mars shows the most fractionated neon.

However, the fractionation of neon should somewhat reflect the amount of water lost to feed the flow of hydrogen that preferentially dragged the light isotope of neon in space. In this case the loss of ^{20}Ne should be correlated to the higher D/H ratio of water, indicative of a preferential loss of H_2 over D_2. One straightforward deduction is that the highest D/H ratio should correspond to the lowest $^{20}Ne/^{22}Ne$ ratio, corresponding to the largest loss of

^{20}Ne. And right away, one is trapped in chaos again. In particular, the Earth, which shows the most fractionated neon, has the least fractionated water relative to the value measured in micrometeorites. In sharp contrast, Venus has the least fractionated neon relative to micrometeorites shows a D/H ratio at least 10 times higher than on the Earth.

Martian water also shows a D/H ratio about 4 times larger than the SMOW value, while the fractionation of neon now looks similar to that observed on the Earth! This gives a hint that the required gravitational escape of hydrogen did use up a higher fraction of water in the Martian environment. But why is this so?

The lack of fractionation of micrometeoritic water on the Earth, which is unique to our blue planet, thus appears as a nice paradox for the origin of life. Indeed, it implies a modest loss of water to trigger the preferential loss of ^{20}Ne, which explains in turn both the large amount of residual water still observed today and the lack of a noticeable increase of the D/H. This required the occurrence of a very efficient process of hydrodynamical escape, which required using up a "minimum" amount of water (c.f., Sect. 19.3).

At the end of this chapter dedicated to a discussion of the most useful criticisms of EMMA, it looks like criticisms are precious sources of new ideas and/or knowledge when one finds ways to answer them. Unfortunately, it is sometime difficult to find a parade. You have to wait for a reply, which might never come to mind, which leaves you in a state of turmoil.

I vividly remember a comment of one of the stars of geochemistry, who told me in June 2000 with a poorly controlled angry voice, while pointing a shivering finger to me: "*you will never explain the characteristics of the noble gases on the Earth*". My neurons were paralysed for a little while by this authoritative shivering finger that I could not stop watching with the greatest attention with my two shivering eyes that started to squint. It took me some effort and the enjoyment of a lunch with Minori Ozima to realise that I was not alone colliding with the stumbling block of the heavy noble gases. In fact, nobody has a clear understanding of this distribution, yet, and the shivering finger should have known about it. At least, SW-sunburns helped us find some hints to the neon problem.

Part IX

Science and Fiction

30 Summary

Surprising EMMA. The main star of this book, besides the Moon, is an obscure contamination of the young Earth that was falling from the sky. It was mostly deposited by invisible tiny cosmic dust grains that can hardly be felt between two fingers. It was neglected for a long time because its composition and the variation of its mass flux with time were not tractable. Therefore, its effects could not be predicted.

These cosmic dust grains, called micrometeorites, are still twirling around us. They are just extremely diluted in the cloud of fly-ashes in which we are permanently trapped, except in a dust-free room. Our beautifully craterized Moon and its spectacular multi-ring impact basins, and the splendid wildness of the Greenland and Antarctic ice sheets from which we extracted this dust, convinced us that this contamination has a surprisingly high visibility. Indeed (i.e., in our view), this is for example the liter of nitrogen that we breathe every few seconds when we are not exercising and the glass of water with its floating ice cubes that you try to sip without swallowing the cold cubes! Moreover it was probably illuminating the night sky through shooting stars that were acting as a myriad of approximately 10 km-long short lasting candles and the luminescent glow of their persistent trails.

I am still astounded by the fits between predictions and observations reported in this book. They were deduced with a simple model coined as EMMA where the play with free parameters was much reduced (see below). This model is based essentially on modern scenarios about the formation of the Earth and the Moon and the $K(t)$ curve conjectured by Hartmann beyond about 3.9 Gyr ago, which is still challenged today. These fits are hard to believe when going so far back in time, when no witness was available to describe what were the early Earth and its night sky. This doubt also extends to all models proposed since the early 1990s for the formation of the atmosphere, which all include adjustable free parameters (c.f., Pepin, 1991; Javoy, 1998; Tolstikhin and Marty, 1998; Morbidelli et al., 2000; Dauphas, 2003).

In this distant past, the boundary between science, fairy tales and science fiction is becoming fuzzy. Indeed, this is an area where scientists have to speculate if they want to progress, whereas science fiction writers have to become scientifically credible. Hopefully the analyses of the lunar and Martian soils

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might help to dissipate this fuzziness. Meanwhile, one has to keep vividly in mind a thought of R.W. Emerson in 1841, which was already quoted by Owens (1992): *"A foolish consistency is the hobgoblin of little minds".*

A slow acquisition of critical data. We tried to constantly feed EMMA with good fresh data to insure its healthy growth. But they were quite difficult to get due to the small size of micrometeorites, and the omnipresent frequently camouflaged terrestrial contamination.

The measurements of high contents of organic carbon in the first aliquot of large micrometeorites that we recovered from Antarctic ices in 1988 (Maurette et al., 1990), helped show that they are related to the hydrous–carbonaceous chondrites (HCCs). As it was already suspected that their mass flux was much higher than that of HCCs, we could foresee their possible contribution to the prebiotic chemistry of life.

At this time we did not realize that micrometeorites destroyed upon atmospheric entry would also play a major role in the formation of the air and oceans, and would open the list of questions discussed in Parts V to VIII. Key measurements of the isotopic composition of both the constituent water of micrometeorites and the oxygen of their refractory minerals were not made. Meager results were available about the isotopic composition of neon in rocks from the upper mantle with regard to the impressive numbers of analyses recently compiled by Ozima and Higarashi (2000). Planetary dynamicists had still to compute the half-lives of comets and asteroids, which allowed the exploitation of lunar cratering rates. Until August 2001, they also had "irrefutable" theoretical arguments requiring that the Moon could only be formed before the end of the formation time interval of the Earth, $\Delta(Earth)$, when the Earth reached about 65% of its final mass. It was then impossible to understand the "micrometeoritic" purity of the atmosphere.

But important data started to be gathered since 1991, including:

- the measurements of the concentration and isotopic composition of neon in Antarctic micrometeorites (Olinger et al., 1990; Maurette et al., 1991; Nakamura and Takaoka, 2000; Osawa et al., 2000, 2002);
- the first direct measurement of the mass flux, φ_0, of large micrometeorites (sizes of about 100 μm) captured by the Earth before atmospheric entry (Love and Brownlee, 1993);
- the first measurement of the isotopic composition of the constituent water of AMMs (Engrand et al., 1998);
- the essential revision of the age of the Moon inferred from the work of Canup and Asphaug (2001);
- the difficult measurement of the nitrogen content of micrometeorites by Matrajt and collaborators (c.f., Sects. 9.1 and 29.6);
- the measurement of the mass flux of micrometeorites reaching the Earth's surface after atmospheric entry, of about 20,000 tons/yr (Duprat et al., 2003);
- the existence of debris-disks around stars.

They helped strengthen our scenario. We could build up some confidence to envision unexpected effects of interplanetary dust particles mostly accreted after the Moon-forming event, which range from the formation of the air and oceans to the birth of life on the Earth.

Beware of the "available parameters space". Even credible models still considered elegant incorporate free parameters, which can be adjusted within reasonable limits as to fit the predictions of the models to the corresponding observations. With EMMA, the possibility to play with free parameters is quite restricted.

Indeed, we have a very narrow margin to play with the four parameters of the only one "accretion" formula used in our work to compute the total amount, $M(A)$, of a micrometeorite species, A, accreted by the Earth, since the time of formation of the lunar crust, $t_1 \sim 4.44\,\text{Gyr}$ (see Sect. 11.2). As shown by Gounelle (2000), this value is given by the product $A(\%) \times 10^{-2} \times [K(t_1) \times \tau \times \varphi_0]$, where $A(\%)$ is the average concentration of A measured in micrometeorites, and the product in the parentheses is an approximate value of the integrated mass flux of micrometeorites captured by the Earth since the formation of the lunar crust at time, t_1. This product is deduced from both the integration of the relative lunar cratering rate, $K(t)$ conjectured by Hartmann, and the present-day micrometeorite mass flux $\varphi_0 \sim 40,000$ tons/year directly measured on impact detectors on board of the spacecraft *LDEF*.

As $A(\%)$, φ_0 and t_1 are just plain measurements, we are thus left with only two parameters that can be eventually adjusted, $K(t_1)$ and τ. However, they are fixed by our choice of Hartmann's conjuncture, which is one of the key backbones of EMMA. We thus directly read the value of $K(t_1)$ on $K(t)$, at $t_1 = 4.44$ Gyr, and the "average" lifetime, τ, of the population of the lunar impactors was inferred from the roughly exponential decline of $K(t)$ with decreasing time. One could be tempted to increase the value of $K(t_1) \times \tau$ by a factor of about 2–3, to reduce the deficit of water predicted by EMMA –we recall that Hartmann still warns that the values of $K(t)$ are known within a factor 10 beyond 3.9 Gyr ago. However, the total amount of the three other species would get higher than the corresponding observed quantities. Therefore, the uncertainty about the value of this product during the post-lunar LHBomb can hardly exceed a factor 2–3.

Exobiology. A unique feature of micrometeorites is that they give the widest variety of chemical pathways that might have been involved in the prebiotic chemistry of life. In the first place they yielded water, the basic fluid of life, which was delivered by the kind of soft diffuse "volcanism" induced by micrometeorites destroyed upon volatilization and/or melting upon atmospheric entry (Part III).

In Part IV, we focused on the role of micrometeorites that survive unmelted upon atmospheric entry, and which possibly functioned as chemical chondritic reactors. They reached the possibly very rare spots of the early

Earth's surface that were the most favorable for the birth of life. In fact, during the first 100 Myr of the post-lunar period, their total number, per m^2 of Earth's surface, per day, reached the astonishingly high value of 30,000!

In Part V, we presented other plausible contributions of this odd micrometeoritic volcanism falling from the thermosphere to exobiology, which probably created the "worlds" of sulfides and, thioesters and the "hell" of kerogen. In our view, it fuelled in particular the functioning of the post-lunar submarine hydrothermal system as a giant chemical reactor with iron sulfides, CO_2 and organics. Without this feeding this system would have been quite sterile in the prebiotic chemistry of life because the Moon-forming impact blew off previous sources of sulfides and carbonates originating from the earlier degassing of the Earth's interior. Moreover, a spectacular shooting star chemistry involving at least two general processes was effective in the early atmosphere (see Sects. 16.2 and 16.3). This surprisingly high diversity of reaction channels induced by micrometeorites makes it almost certain that they played a dominant role in the origin of life on our blue planet.

In all previous simulation experiments about the prebiotic chemistry of life (involving the polymerization of amino acids, for example), the most favorable "adjustable" ingredients were selected to speed up reaction rates, without worrying too much about their problematic existence and/or delivery to the early Earth. We depart from this approach, while only using the limited choice of ingredients such as ferrihydrite that we could characterize in micrometeorites with the present-day techniques of microanalyses. This is a severe limitation. Nevertheless, it is counterbalanced by the great advantage of knowing that they were delivered in prebiotic conditions.

Comparative planetology. A variety of predictions were made and some of them appear to be validated. For example, in 1999, we realized that we could not explain the amazing micrometeoritic purity of the Earth's atmosphere without assuming that the Moon was formed near the end of the formation time interval of the Earth, thus being younger than previously thought –i.e., on the usual time scale where today is zero. This bold deduction that we never dared to publish ran against conventional views. It is now comforted by the improved 3D model of formation of the Moon proposed by Canup and Asphaug (2001). In the field of Earth's sciences, we predict the right micrometeoritic "purity" of the atmosphere of the Earth as well as the iridium and sulfur contents of rocks from the upper mantle. They represent new constraints that should help in the understanding of several key processes that fashioned the early history of the young Earth (Part VI).

These fits between predictions and observations also support previous works of colleagues, which are still not completely accepted. They include:

– the description of the period of early heavy bombardment beyond 4 Gyr ago, as conjectured by Wetherill (1975) and Hartmann (1999);
– the noble gas chronology of important early solar system events (Ozima and Podosek, 2002);

- the new impact model proposed by Canup and Asphaug (2001) to describe the formation of a younger Moon;
- the fast degassing of the terrestrial mantle (Sarda et al., 1985);
- the physics of the Moon-forming impact proposed by Ahrens (1993) that deals with the mechanical effects of this impact, and which should soon include its thermal effects.

Other challenging prospects and problems ahead. EMMA looks like a kind of unifying scenario that accounts for very different mysteries specific to the first 500 Myr history of the Earth. Most colleagues feel uneasy about this characteristic. A literate reviewer brillantly summarized their feeling. He went on reproaching that EMMA is presented as a "Panacea Universalis" and he rejected for this reason our last paper. However, there is a long list of still mostly unanswered challenging questions, such as:

- The relationships between the very different model ages determined with the Hf–W and I–Xe chronometers;
- The prebiotic chemistry that gave birth to life, and which results from poorly understood synergetic effects between water, organics and minerals surfaces behaving as both molecular adsorbent and catalysts. In this context, nanomaterials, such as the nanotubes of ferrihydrite found in unmelted micrometeorites, or the colloidal suspension of kerogen particles probably deposited in early seas, were probably activating a new type of prebiotic chemistry, which is totally ignored as yet;
- The stumbling blocks of the chemical and isotopic compositions of the heavy noble gases in the Earth's atmosphere;
- The huge amplification of the flux of lunar impactors at the time of formation of the Moon. It implies a change in the early configuration of solar system bodies that we do not apprehend;
- The huge difference in the distributions of D/H ratios measured in AMMs and the tiny SMMs collected by NASA in the stratosphere;
- The extrapolation of EMMA to Mars and Venus. Here, we hit the severe difficulties of estimating both the date of the unavoidable merging of the last planetary embryo on these planets, the survival of an ancient regolith system on Mars and the intracktable redistribution of the surface material that confuses surface analyses.

"Leonids" at Concordia and "Stardust" particles. The search for micrometeorites from the Leonids meteor showers trapped in the 1966 snow layer deposited near the Concordia station, should give a boost to *Micrometeoritics* if it succeeds. It should allow testing definitively the deduction that most micrometeorites do originate from comets and not from asteroidal collisions (c.f., Chap. 22). For a long time to come, it would yield the only large dust grains with a well-certified cometary origin, and with sizes of about 50–200 μm, unless the *StarDust* spacecraft (Stardust-web; Brownlee et al.,

2004) successfully returns to the Earth (via parachute recovery of the sample return capsule) large dust grains from comet Wild 2, on January 15, 2006.

Dust flux monitoring on the spacecraft during the encounter with the comet, on January 2, 2004, already suggests that about 500–1000 cometary dust particles with sizes $\geq 15\,\mu m$ (and many more smaller grains) were collected by impact into a silica aerogel (Zolensky et al., 2004). This is not exactly an intact capture experiment because these particles were impacting the aerogel at speed of about 6 km per second. They thus suffered an unavoidable sharp aerodynamical braking in the aerogel, which is a kind of high-density atmosphere that possibly fragmented and heated them up. However, it is likely that the very short duration of the pulse heating of the particles in the aerogel helped to protect them. This will be a spectacular and important milestone that will give another boost to *Micrometeoritics.*

A comparison of the largest *Stardust* particles with the Leonids and the Concordia micrometeorites would certainly be most useful in many respects. In particular, it should definitively ascertain the cometary origin of the dominant sporadic flux of micrometeorites collected everywhere in Antarctica, even with a simple empty can –they were used to scoop the glacial sand that accumulates in the dominant downwind side of rock resting and/or extruding from the surface of a blue ice field in the Transantarctic mountain– c.f., Harvey and Maurette (1991) for a review of these collections that have several limitations.

If so, the very cold and ultra-clean snow deposited in central Antarctica up to a depth of about 100 m would become the inexhaustible cometary dust particles collector of a giant *Stardust* spacecraft, the Earth. Comet particles could be recovered directly by melting this snow collector without the need for any additional cleaning, which is always a source of contamination.

The investigation of the carbon chemistry of the Leonids might give new clues about the prebiotic chemistry of life, because their carbonaceous component should be the most pristine one delivered to the Earth's surface. Furthermore, the crystalline-type *Leonids* should contain a pure solar wind component of heavy noble gases (Ar, Kr and Xe). Indeed, their short flight times of a few centuries in the interplanetary medium was too short to spoil them with a SEP component, which is present in sporadic micrometeorites, in the lunar soil and in gas-rich grains from a variety of micrometeorites –the fine-grained AMMs cannot be used for this purpose, because they already contain a "primordial" component of noble gases that would spoil the SW component.

If so, this component might yield new hints about the composition of the heavy noble gases in the solar wind if each of these tiny crystalline collectors can be individually analyzed. This might help reach some of the major objectives of the Genesis space mission (they are outlined in the remarkably concise introduction of Barraclough et al., 2004). They might now be difficult to achieve with the solar wind collectors of the mission, if they have been too damaged and/or contaminated during their rough landing on the Earth in January 2004.

The *Stardust* particles cannot be used to tackle this problem, because their flight times in the interplanetary medium before their capture by the aerogel collector were much too short (about 1 minute). On the other hand, these very short flight times ensure that their initial noble gas record is unspoiled by recent SW and SEP noble gases. Therefore they should bear unique information not available with any other material about the early history of cometary dust grains before their capture by cometary ices.

Epilogue: The Birth of "Micrometeoritics"

This book is an attempt to blend an extended and cross-disciplinary research paper about an initially neglected obscure cosmic dust contamination of the early Earth into a kind of cosmic detective investigation, which should be comprehensible by the space sciences community and undergraduate students in general. The major objectives were to:

– give a taste of *Micrometeoritics*, a discipline which was pioneered by Donald Brownlee in the early 1960's, and which addresses problems as different as the formation of the early Earth's atmosphere, the origin of life on our blue planet and the cataclysmic period of the *late heavy bombardment* of the inner solar system;
– illustrate how new disciplines flourish on neglected problems, chaos, bold bets, incessant questioning and a stubborn resistance to conventional wisdom.

In 1960, the field of cosmic dust studies was rightly disregarded as poor science. Indeed, particles claimed to be cosmic dust since the 1920s were in fact terrestrial fly ashes, and some of them look very much like the dark charcoal-looking micrometeorites collected today. They are still found in any collection of micrometeorites recovered from blue ice fields or surface snow collected around scientific station in Antarctica, because one has to move at least with a snow-mobile that generate such ashes –they are very rare in slabs of snow recovered from a deep trench at Concordia. They have been coined "*pseudomicrometeorites*" by Osawa et al. (2001). Indeed, beside their anomalously high carbon contents, their chemical composition might sometimes mimic the primitive chondritic composition.

The only trustable cosmic dust grains were cosmic spherules (e.g., melted micrometeorites) made of an alloy of FeNi, unknown in terrestrial rocks. Murray and Renard (1883, 1891) already used this criteria in the late 1850s –Murray was one of the participant scientists in the famous 1873–1876 *HMS Challenger* oceanographic expedition. They investigated Pacific red clays by running a hand magnet through deep sediments collected during the expedition. They deduced that they were cosmic spherules because their FeNi core was very different from iron found in volcanic rocks, which is strongly depleted in Ni.

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This situation was due to the lack of both techniques of microanalysis and good criteria to identify the extraterrestrial origin of particles with irregular shapes (i.e., such as the "chondritic" chemical composition), which were just on the verge of being developed for the analyses of lunar samples to be returned to the Earth by the Apollo missions. So, Brownlee had to fight mostly alone until about 1974, when he succeeded,using a U2 aircraft, to collect in the stratosphere very small micrometeorites with sizes of about 5–15 μm. At this time, he was armed with a new scanning electron microscope equipped with a powerful system of X-ray microanalysis, which was funded for lunar sample studies. Carbonaceous chondrites were also much better known. He could thus convincingly argue for the extraterrestrial origin of the new stratospheric micrometeorites (SMMs), while showing that they bear relationships to this group of the most primitive meteorites.

In the early 1980s, these tiny SMMs started to interest a few other groups, mostly associated to the McDonnell Center for the Space Sciences (Washington University) founded by a charismatic leader R.M.(Bob) Walker. Fraundorf (1981) reported transmission electron microscope observations of the particles. They were further extended by Bradley in a long series of papers that was initiated when he was working with Brownlee (Bradley et al., 1983).

The team of Ernst Zinner was the first of about 200 groups investigating extraterrestrial materials at this time to be equipped in 1982 with the first version of the powerful ion microprobe conceived by Slodzian (Castaing and Slodzian, 1962; Slodzian, 1980). After a hard but efficient search for funding, Bob bought the first model of this instrument (IMF-3f), because he was deeply convinced that it has a unique capability to hunt for interstellar dust grains in meteorites and micrometeorites (Walker, 1993; Bernadowicz and Walker, 1997; Messenger and Walker, 1997). The instrument was delivered in June 1982 and in 1983 (Zinner et al., 1983) could report on their exciting observation that about 1/3 of the SMMs were showing D/H ratios higher than the SMOW value.

The most recent version of this instrument, also conceived by Slodzian (see Sect. 28.2, 2nd Subsect.) and named subsequently "NanoSIMs", has an amazingly high spatial resolution of about 100 nm. It was again bought by Bob in 2000 and was installed at WU the following year. It allowed Messenger et al. (2003) to discover last year that these small bits of extraterrestrial matter contained even much smaller bits of micron-sized genuine interstellar silicates. They could be found with the ion-imaginining system of this microprobe even though they are quite rare (e.g., 6 out of 1036 silicates).

In 1982, we naively thought about reinforcing this stimulating SMMs consortium. The first step was to visit the laboratory of Donald (Don) Brownlee, who warmly welcomed us with a delicious piece of wild salmon to his beautiful house boat in the bay of Seattle. After this impressive welcome, I happily submitted my first proposal to recover unmelted micrometeorites about 1,000 times heavier than a typical SMM from Antarctic ices –Don subsequently called them *giant* micrometeorites (Maurette et al., 1989). But the two reviewers rejected this proposal, first arguing that the project was dangerous because the blue ice fields were loaded with crevasses, even though I wrote that one member of the team (M. Pourchet) was a glaciologist and certified mountaineer already familiar with this zone.

One of them kindly warned us "*you will hardly find unmelted micrometeorites"*. This warning should have been taken quite seriously. It was supported by the findings of Brownlee himself, who studied the magnetic cosmic dust that he started to recover from deep-sea sediments in 1976, at the center of the Pacific Ocean, with a spectacular 300 pound magnetic rake. He found that this cosmic dust was mostly composed of cosmic spherules with sizes $\geq$100 µm (see Fig. 5), with a very small admixture of "unmelted" micrometeorites ($\sim$1%), which were possibly confused in these earlier times with "incompletely-melted" micrometeorites containing relict minerals. Indeed, truly unmelted fine-grained micrometeorites are both only weakly magnetic and quite friable. Therefore, they can hardly be recovered during such a harsh magnetic raking that can only extract hard and magnetic particles from the sediments.

The ratio of unmelted to melted micrometeorites of about 1% was even considered to be compatible with the predictions of modelling of frictional heating upon atmospheric entry. So, the best move would have been to follow the kind advice of the reviewer and to quickly discard this unsound project. However we persevered, and found that this ratio was severely underestimated. Duprat et al. (2003) measured a value about 100 times higher ($\sim$1) in their most recent Concordia collection of highly friable micrometeorites. Bonny in the late 1980's helped understand why these predictions were not reliable (c.f., Sect. 22.2).

The other reviewer also added a concise and helpful statement: "*You will find nothing new, because your tiny bits of extraterrestrial dust will just turn out to be microscopic fragments of meteorites at least several millions times more massive*" –he probably translated into a polite sentence the thought that it would be useless to waste taxpayer money hunting for micrometeorites when so much similar material was available in the world collections of meteorites. Last year, a high-ranking French cosmochemist made a friendly statement still warmly supporting this obsolete criticism: "*Give me a hammer, a meteorite and I'll made millions of micrometeorites*". Gero Kurat, who is a real geologist and mineralogist who knows about using a hammer to collect pieces of rocks from the upper mantle all around the world, told me: "*Don't worry. This man does not know about handling a hammer. It is already very difficult to get a fine-grained dust crushing a rock with a hammer. But it is inconceivable to get with this primitive technique inherited from Neanderthal man, a size distribution that peaks around 100–200 µm*".

However, thanks to the energetic support of a few wide-minded colleagues (including the glaciologists Claus Hammer and Michel Pourchet and the radioastronomer Jean-Louis Steinberg), and in spite of the remarkable total lack of support of one of the previous directors of my own laboratory (he rejected with a marked irritation my humble request for an additional funding of about 3000 dollars), we finally got the adequate funding of INSU (Institut National des Sciences de l'Univers) to collect micrometeorites in Greenland. The success of this operation (Maurette et al., 1986, 1987) opened the way for an important and constant logistic and financial support of "*Expéditions Polaires Françaises*"(now called IPEV), which was completed in Greenland by the University of Copenhagen and the "*Greenland Geological Survey*". In January 1988, we successfully recovered about 20,000 large unmelted Antarctica micrometeorites from about 100 tons of blue ice in about four weeks of summer field operations. Even more striking, each one of these large AMMs had a mass equivalent to the total mass of SMMs collected from 1974 until 1989.

In the following decade, our findings, altogether with those obtained by the SMM consortium, reinforced the field of *Micrometeoritics* that now deals with unmelted micrometeorites recovered in the approximately 5 μm to 800 μm size range. All investigators have to be experts about the microhandling of tiny dust grains in ultra-clean conditions, and their analyses with microbeams techniques, which are frequently exploited near their limit of sensitivity. They have also to have a few good friends in various disciplines, who support them, even though they might get furious sometimes about some bold bet, pointing out that "*a car is a car*".

The Japanese made important collections of Antarctic micrometeorites near their Dome Fuji station and around the Yamoto Mountains. They simultaneously gathered a large consortium of investigators from 13 Institutes, equipped with powerful instruments of microanalysis, to study these particles. The mineralogical studies of Gero Kurat, the accurate noble gases analysis of carbonaceous chondrites and AMMs reported by Tomoki Nakamura and collaborators, the generous help of André Brack in exobiology and the very detailed and useful review of this book by Mike Zolensky were priceless.

There was a succession of strong emotional feelings along our bumpy road back into the mysteries of our distant past with these *anonymous-invisible* particles of cosmic dust being exploited as unique probes of early solar system processes. The first one was the immense happiness to discover that the first reviewer of our first proposal was so wrong, when we discovered so many unmelted micrometeorites in the Cap-Prudhomme blue ices (see Fig. 7). The second one was a strong deception (carefully camouflaged into pseudo-happiness) with the simple classification of Antarctic micrometeorites, only related to the relatively rare CI- and CM-type chondrites that represent about 2.5% of the meteorite falls. Indeed, we first felt discouraged, because our major objective was to find new objects not represented as yet in the meteorite collections, which already includes at least about 135 distinct groups of meteorites. However, we slowly warmed up, while progressively realising that this odd feature was a unique characteristic of the Cap-Prudhomme micrometeorites, which was going soon to fully invalidate the pessimistic views of the second reviewer of our first proposal. At least, they were not just tiny bits of much more massive meteorites originating from interasteroidal collisions!

At this stage, being still beginners in exobiology, we followed the vogue to consider that only extraterrestrial materials that survive unmelted upon atmospheric entry can contribute to the prebiotic chemistry of life. We thus neglected those destroyed through volatilisation and/or melting –e.g., about 75% of the incoming flux of micrometeorites. In this earlier period, we developed in particular the concept of tiny micrometeoritic reactors for prebiotic chemistry without realizing that they might have been somewhat poisoned by their inert kerogen.

But Cécile Engrand in our team, with the help of Etienne Deloule, awakened us with brutal force in 1997. They used the ion microprobe of Slodzian available at *Centre de Recherches Pétrographiques et Géochimiques* (Nancy) to show that from all extraterrestrial objects known at this date only the constituent water of AMMs gives an isotopic composition similar to the standard value, SMOW, measured for the terrestrial oceans. This led us to simultaneously realise that the constituent neon of micrometeorites also fit the solar isotopic composition expected for early neon on the Earth. A small fraction of this neon is still locked in rocks from the primitive upper mantle. Since the early 1990s, it is supposed to originate from the degassing of the building material of the Earth and not from the subduction of an oceanic crust loaded with unmelted micrometeorites.

The new world created by micrometeorites destroyed upon atmospheric entry, and generating a kind of new volcanism erupting softly and silently from the sky all around the Earth, was just on the verge of being explored. We started to wonder whether or not a giant storm of micrometeorites, effective after the formation of the Moon, delivered the ocean water, as well as the other volatiles of the atmosphere. At first, we were quite pessimistic because the concentrations of volatile species in micrometeorites vary greatly –e.g., their neon content is about 10^5 and 10^7 times smaller than their nitrogen and water contents, respectively. Moreover, we met strong opposition in each one of the disciplines we were intruding upon, except exobiology. Colleagues paved our way with criticisms that we could hardly answer quickly due to our ignorance. Some of them ended up being totally irrelevant. Some of them unexpectedly initiated new unforeseen applications of EMMA instead of invalidating this scenario! But a few of them have still to be fully answered as indicated in Chap. 29, which is a potpourri of these criticisms.

These huge differences in the abundances of volatiles in AMMs led to the concept of the micrometeoritic purity of the atmosphere. In fact, the enormous difference of 10 million between the content of neon and water in AMMs was rightly tuned to account for both their total amounts and their abundances relative to nitrogen in the atmosphere. Since that time, “conventional wisdom” could not stop us anymore. Indeed, we discovered while attempting with great difficulties to answer the earlier criticisms of EMMA, that the *stars* of a discipline often assimilate their own beliefs to hard facts, and this frequently ends up sterilising science. Now, we do not hesitate to grapple with major problems, even though we are just beginners in the corresponding disciplines.

This cosmic detective investigation in our distant past was based on a succession of bold bets. However, they were constrained whenever possible with a minimum of scientific rigor. For example, we first checked the validity of EMMA with four volatiles in the Earth’s atmosphere. But we next moved to the very different environment of the terrestrial mantle with iridium, one of the most refractory elements, to check a second time its validity.

We feel it appropriate to close the science fiction part of this book with a last and very loosely constrained bet, which still belongs to the nightmare world of Dante, the ecologists and the reviewers of our future papers. In Sect. 16.2, we tentatively outlined how kerogen, which is the dominant carbonaceous component of micrometeorites and hydrous–carbonaceous chondrites, can be recycled through a chain of diverse processes into kinds of cosmic crude oil, which oddly enough would be generated by “dead” micrometeorites!

Crude oil spilled upon the wreck of the Exxon Valdez oil tanker triggered the formation of spectacular and noxious *black tides*. It started floating and spreading over the surface of the oceans for long months, and ended up generating odd shaped sticky deposits of fuel oil along coastlines and bare foots, called *pellets, blankets, sheets, shits, beans, cookies, etc.* They were digested in about 1–5 years by microorganisms that thrive on them and/or dissolved with organic solvents. But in the absence of life, and consequently of the chemical industry providing organic solvents to clean your toes, they would be among the most insoluble and durable carbonaceous material known, yet. Consequently, in Hadean time, before the birth of life, the light fraction of this cosmic micrometeoritic crude oil would have floated “forever”, making a kind of gigantic ugly black tide spread over the whole of the Earth’s surface.

This cosmic rain of crude oil and water reached every cm^2 of the early Earth’s surface, including the early continents if they ever existed. The resulting black tide, spreading all around our blue planet, might have camouflaged its wonderful colours with a dull dark varnish, which possibly also affected the greenhouse effect! It is fascinating to wonder whether there is a chance that this gigantic “cosmic” black tide, which would quickly *destroys* life to day, was the dominant process in the prebiotic chemistry of life. After the worlds of sulfides and thioesters, the fascinating dark hell of *kerogenetics* appears on the horizon.

When I was a student, I had the great chance (and/or the bad luck?) to meet a great French humorist, Pierre Dac, during the preparation of an examination in Physics. I inevitably failed at the session of June, because during the three weeks that preceded this examination, I was fully busy almost every evening keeping an eye on "Nanar", a famous approximately 5 cm long gudgeon (i.e., a freshwater fish related to the carp), which was caught in the Seine River running through Paris –this was certified on a very old looking parchment manuscript. Nanar was quite happy to swim elegantly in a ∼20 liter glass jar, placed right at the center of a big tent, which could accommodate at most about 20 (±10) pairs of excited human eyes, which I would now consider as a straightforward by-product of micrometeorite accretion.

The tent was set on *Esplanade des Invalides* right at the Centre of Paris and about 500 m plus about 100 stair steps away from the door of my room. The challenge for Nanar was to compete (very successfully) with a 5 m long whale, "Jonas", which was on exhibit in a nearby much bigger circus. The entrance fees to see Jonas and Nanar were worth about three and one beer, respectively. Consequently, Nanar ended up being the favourite of students. Dac, who got to know during these long evenings that Nanar was quite clever, and also that I might attempt to be a scientist, came upon a brilliant thought, which now so well applies to the studies described in this book: "*the most difficult thing when you are right is to prove that you are not wrong*".

The reader, who made the effort to read this book up to this fourth paragraph before end might have possibly caught on that some scientists act as incurable and brutal drug addicts of the unexpectedness. They only care about the conventional wisdom of their few friends and are great masters in burying definitively under huge piles of papers and unopened mails the criticisms of the reviewers who reject their papers with the kind and most useful statement that "I am not convinced by the authors".

They function as natural scientists, looking with the greatest excitation at the wild cosmos, when they are not obliged to look for long monotonous hours at the screen of their PCs and/or to take a happy siesta either on a fine-grained warm sandy beach or in the warm Jacuzzi of John Bradley. They dislike artificial and sterile barriers between scientific fields that were mostly inherited from Napoleon and Bismarck, and which are the building blocks of a myriad of institutions, scientific journals, scientific meetings, and scientific abstracts extended or not.

These barriers might be fiercely guarded by some of the "stars" of each discipline, who want to own a scientific journal and its associated annual meeting. Conflicts within a discipline end up generating other journals and meetings that treat exactly the same subjects. These barriers between disciplines and men, and the deadly proliferation of second rate scientific literature that they propagate, are becoming a major obstacle to scientific progress. Hopefully, they will be shattered away by the Internet and the new ways of communicating pioneered by the *Johnson Space Center* of NASA (and its associated Lunar and Planetary Science Institute) in Houston, unless a cataclysm electronic virus destroys the Web.

Otherwise, the only alternative would be to follow a brilliant innovative suggestion of Sir Martin Rees (Master of the famous *Trinity College* of the University of Cambridge): *"Researchers might find more intellectual stimulations reading good science fiction books rather than a second rate scientific literature"*. Unfortunately, the initial English quotation of Rees was first translated into French by a French (Barthelemy, 2004), and then back to English by another French (c.f., the previous sentence). Therefore, as French cannot master the subtleties of the elegant English language spoken at the University of Cambridge, we might be far away from the original thought of Rees, and therefore back to full chaos again, just eleven words away . . . from the real end of this book.

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