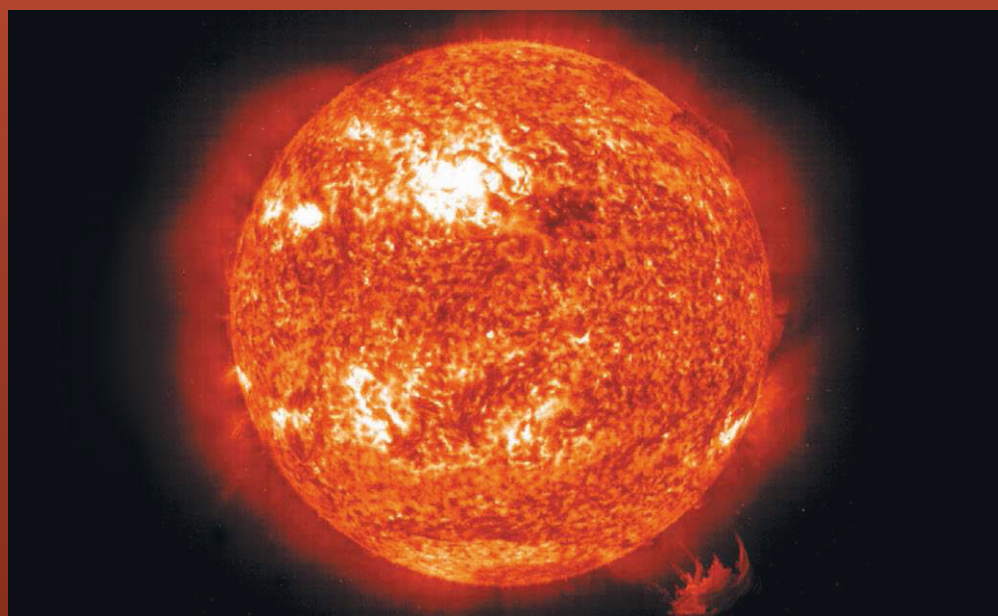




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Space Weather, Environment and Societies



J. Lilensten - J. Bornarel



Springer

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by

Jean Lilensten

*Researcher (CNRS), Planetary Laboratory of the Grenoble University
(Université Joseph Fourier), France*

and

Jean Bornarel

*Professor Grenoble University (Université Joseph Fourier),
Physics Spectrometry Laboratory, France*



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(Contact : Tél.: (33) (0)4 76 51 46 95 - Fax: (33) (0)4 76 51 45 79

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Professor at the Joseph Fourier University, France

The "Space Weather, Environment and Societies" Reading Committee included:

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TABLE OF CONTENTS

Introduction	XI
Acknowledgements	XIII
Chapter 1 – The Sun.....	1
1. The formation of the stars and the Sun	1
2. The characteristics of the Sun	7
3. A representation of the Sun	11
4. The internal structure of the Sun.....	11
5. The photosphere, solar radiation, the solar wind	17
6. The thermal profile of the solar atmosphere	24
7. Solar dynamics	27
7.1. Sunspots. The solar cycle. Prominences and eruptions	27
7.2. Coronal holes. Fast wind	37
7.3. The large-scale structure: coronal streamers	40
7.4. Coronal mass ejections	42
7.5. An index of solar activity	45
8. The Sun: at the source of space weather.....	46
Chapter 2 – The Earth	49
1. The Earth within the solar system.....	49
2. The internal structure of the Earth: the geomagnetic field.....	53
3. The atmosphere of the Earth	58
3.1. The homosphere	58
3.2. The heterosphere, the thermosphere, the ionosphere.....	61
4. The magnetosphere	68
4.1. The magnetosphere and the network of currents	70
4.2. The polar lights.....	79
4.3. Magnetic storms and sub-storms.....	86
4.4. High altitude lightning flashes	89
Chapter 3 – Toward a space weather	91
1. The consequences of solar agressions on our technological environment	93
1.1. Pipelines.....	93
1.2. Transmission of electricity	94
1.3. Railways	97

1.4. Telecommunications	98
1.5. Spacecraft launches.....	101
1.6. Satellite flight	103
1.7. The reentry of spacecraft into the atmosphere	110
1.8. Space debris and its effects.....	111
2. Other impacts of solar activity	114
2.1. Biological effects	114
2.2. The climate	117
2.3. Insurance companies.....	119
2.4. Military defence	120
2.5. Tourism and education of the public	121
3. Space weather in order to forecast	121
3.1. Its birth certificate	121
3.2. A science that is still in its early stages and its applications.....	125
3.3. Toward maturity: the intense space weather storms of October-November 2003.....	128
Appendices	133
1 – The density and kinetic energy of a gas	135
2 – The internal nuclear processes of the Sun.....	138
3 – The electromagnetic field.....	141
4 – The dipolar magnetic field	145
5 – The doppler effect and the wavelength.....	150
6 – Photometric quantities.....	153
7 – The blackbody.....	157
8 – A comprehensive view of electromagnetic waves	160
9 – The magnetic field and the movement of particles, frozen plasma and fields.....	163
10 – Kinetic pressure and magnetic pressure	166
11 – The Coriolis force.....	167
12 – Kepler's laws	171
13 – Sidereal time and solar time.....	174
14 – The characterization of magnetic activity by means of indexes.....	177
15 – The variation in molecular concentration with altitude	179
16 – Elements of atmospheric chemistry.....	181
17 – The movement of a charged particle in a magnetic field tube.....	184
18 – The calculation of the position of the magnetopause.....	187
19 – The planets of the solar system in the glare of the Sun.....	189
20 – The Moon in the glare of the Sun	198
21 – Comets, meteors and asteroids in the glare of the Sun.....	201
22 – Orbital parameters	205

23 – Space weather instruments.....	209
A few useful constants	217
References	219
Word glossary.....	221
Glossary of names, acronyms and logos.....	233
Index.....	239

INTRODUCTION

Space Weather, Environment and Societies illustrates the unexpected effects of solar activity on human activity. Although the characteristics of our star have, on the whole, remained pretty well unchanged throughout the history of mankind, lately its mood swings, and considerably varying ejection of matter and radiation have had disruptive effects on our technology-based society. Data and energy are transmitted using the same vehicles as in nature: charged particles and electromagnetic waves. This means that whole areas of our technical environment are concerned: telecommunications, production and transmission of electricity, transportation of oil, railways, positioning systems, airplanes, satellites... Incidents and accidents are on the rise, hence the need to forecast solar activity with precision and to quantify the response from the terrestrial environment: this is the objective of space weather.

The first chapter of the book introduces the Sun and explains its emissions of electromagnetic waves and particles, particularly in the direction of the Earth. The second chapter explains how the ionized environment and the magnetic characteristics of the Earth form natural barriers against fatal radiation and showers of particles. The third chapter shows how fragile our industrialized societies, with their electrical networks, pipelines, airplanes and so on, have become in the face of natural phenomena.

A well informed or hurried reader can read *Space Weather, Environment and Societies* in one sitting. This would be akin to reading a novel illustrated with diagrams and wonderful photographs. Included with the text are footnotes that provide historical, technical and scientific details. More detailed explanations are to be found in the 23 appendices. Some of these are aimed at the reader whose scientific level corresponds to the first cycle of university with the aim of consolidating his comprehension of a physical phenomenon. Others, given here purposely to avoid overloading the main part of the text, provide further information on the relationship between the Sun and the atmosphere of other planets or the detection apparatus required for space weather. The meanings of words or symbols can be found in the glossary. The bibliography of websites and books, the index and the table of contents are intended for the reader who will use this work as a reference tool.

We hope that *Space Weather, Environment and Societies* will go toward furthering the knowledge of and respect for the wonderful world that surrounds us.

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The authors

To my family, to Geneviève, Lola and Maël

J. L.

Chapter 1

THE SUN

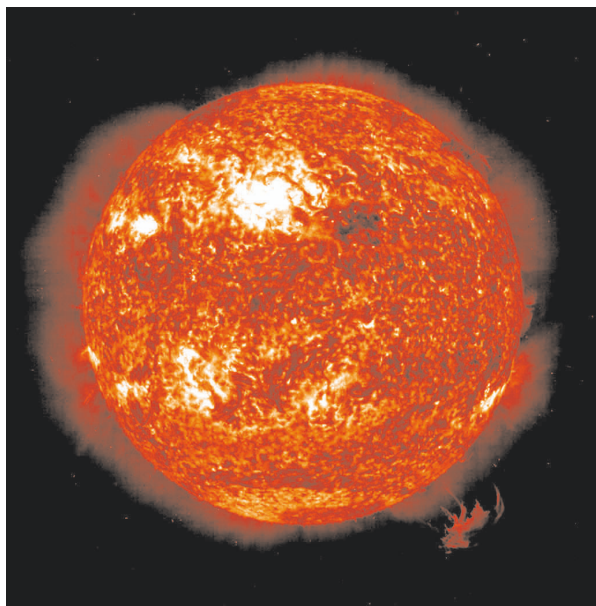


Figure 1.1 - The Sun as seen by EIT from the SOHO satellite

The Sun is at the origin of the energy we receive, the very origin of life. We believe we know it well and yet it has only been a short time since we first became fully aware of its behavior! The first spectral studies to determine its chemical composition were carried out during the nineteenth century. In 1945, the appendix to the Manhattan project concerning the first atom bomb provided an explanation for the internal source of the Sun's energy. Finally, in 1995, the SOHO satellite (SOlar Heliospheric Observatory, ESA/NASA) was launched. Since then, findings have accumulated. So where do we go from here?

1. THE FORMATION OF THE STARS AND THE SUN

One only has to look up at the sky on a clear night to see that, in some parts, matter appears to be far more condensed. What can be seen are primarily clouds of gas,

planets from our solar system, stars or galaxies. Each of these galaxies contains a huge number of stars. Our own galaxy, known as the Milky Way, is made up of about 100 billion stars. Also, galaxies come in clusters. In our "Local Cluster", there are about thirty small galaxies around two giants: the Nebula of Andromeda and the Milky Way. Light takes between 80,000 and 100,000 years to travel from one end of the Milky Way to the other so the diameter of our galaxy is said to be between 80,000 and 100,000 light years¹. It would, therefore, take 3 to 4 million years to travel across the Local Cluster.

The Sun is not an exotic object in the universe, but merely a star amongst many others. But how are these stars formed? From the hydrogen and helium gases that were formed abundantly at the birth of our present universe, and a detonator. The latter is a shock wave that spreads beyond the blast of an explosion. The explosion is usually that of another star. This immediately raises the problem of the first generation of stars. According to the current standard theory, the shock wave may have been the one associated with the first explosion, the famous "Big Bang" at the origin of our universe.

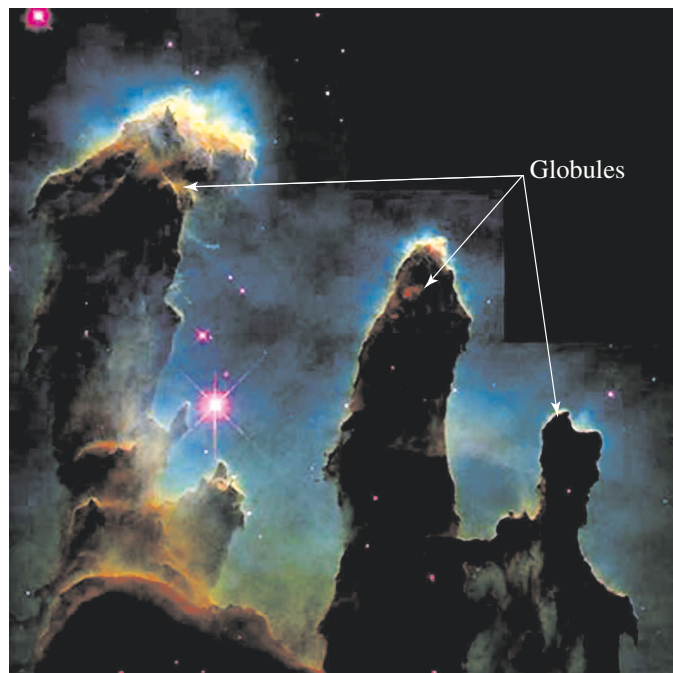


Figure 1.2 - A cloud of molecular hydrogen in the Eagle nebula.
The photograph was taken by the WFPC2 on the Hubble space telescope
This is a star incubator. Some globules can be seen on the edge of the long fingers of gas (credit J. Hester and P. Scowen – Arizona State University; NASA).

¹ One light year is 9.461×10^{12} kilometers.

Once the mechanism has been triggered, gravity keeps it going. Matter is more abundant in a compressed area, therefore the forces of gravitational attraction² are higher. This sector, which spreads over tens or even hundreds of light years, attracts the surrounding isolated particles and the whole area soon becomes opaque to the light of neighboring stars. The embryo of a star goes through a cooling phase during which it drops to about 10 degrees Kelvin, because it cannot be heated by outside glow. Inside, however, as the density increases, so do the impacts³. Denser globules appear locally and here, the collisions are sufficiently numerous for the chemical reactions between atoms to create various molecules. For a while, the heat produced by these impacts offsets the lack of heat due to the opacity. This is the isothermal phase. When the concentration increases from about 10^5 to 10^{11} atoms per cm^3 , –which is still quite a considerable vacuum compared with the 10^{19} molecules per cm^3 found in our terrestrial atmosphere at sea level– the infrared radiation emitted by the internal collisions can no longer escape: all the radiation emitted from within the cloud is reabsorbed by the cloud; the energy remains enclosed and the temperature of the cloud of gas increases to about 100 degrees Kelvin. The density, too, increases due to the effect of gravitation. On the one hand, gravity compresses the star and, on the other hand, the heat given out by the collisions slows down the compression⁴. When the concentration of particles reaches 10^{14} atoms per cm^3 , the two effects balance each other out: the dynamic collapse of the cloud stops over an area equal in radius to about five times the average distance from the Earth to the Sun. The volume thus defined is known as the first stellar nucleus⁵.

However, the external parts, attracted by gravity, compress this first nucleus. The concentration and temperature in the center increase progressively to 10^{16} atoms per cm^3 and 2,000 Kelvins. These values are high enough for the diatomic molecules of hydrogen to separate into hydrogen atoms. The separation consumes energy, and this reduces the temperature of the first nucleus. The pressure bearing the mass of the cloud decreases and this triggers a second phase of dynamic collapse. When the pressure reaches 10^{24} atoms per cm^3 (about the same as liquid water under normal

2 The law of gravitation expresses the fact that two homogenous and spherically symmetric masses m and m' placed at a distance d from each other (centers of gravity in Γ and Γ') attract each other in the direction $\Gamma \Gamma'$ with forces of magnitude $F = G \frac{mm'}{d^2}$, where G is the universal constant of gravitation ($6.672 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ in International System units, i.e. with masses expressed in kilograms, distances in meters and forces in Newton).

3 See appendix 1 for the thermodynamic link that associates the number of impacts with pressure and temperature.

4 The heat created by the impacts corresponds to infrared radiation, or photons, of a momentum $\frac{h\nu}{c}$ (as a module) which create over a unit of area a pressure called "radiation pressure". This pressure plays a part in the slowing down of the cloud compression.

5 The adjective "stellar" makes it possible to distinguish it from the atomic nuclei to be found further on. Within this first nucleus, electromagnetic forces play a part that we shall not mention here.

conditions) and the temperature 100,000 Kelvins, thermal pressure is once again sufficient to balance gravitational forces leading to the formation of a second stellar nucleus of a few solar diameters. About 100,000 years elapse between the appearance of the shock wave and the formation of the second stellar nucleus

The second stellar nucleus withstands the forces of internal gravity until the temperature at the core exceeds 10 million degrees. The collisions then become so violent that in spite of the electrostatic forces that repulse them, the nuclei of hydrogen come into contact with each other. Nucleons combine and form first deuterium and then nuclei with four nucleons: helium⁶. A nucleus of helium, coming from four nuclei of hydrogen via a nuclear reaction, is lighter than those four nuclei of hydrogen: the difference in mass has turned into energy. The mass of hydrogen is 1.00797 grams per mole⁷ while that of helium is 4.0026 grams per mole. The difference in mass for one mole produces energy of 2.6352×10^{15} joules, i.e. enough to supply 2 billion 100-Watt lamps for more than 7 hours... A star is born!

Many observations can be explained from the above description. A more complete model would have to take into account the effect of rotation on the cloud in which the star was formed. In the universe, rotation is a generalized way of consuming energy and can be found at all scales, from the largest (that of galaxies) to the smallest (that of atoms and molecules) without forgetting the rotation of the planets around the Sun, on their axis or the rotation of the Sun on its own axis. The establishment of a complete model including rotation is beyond the scope of this book (the bibliography includes a few titles that provide an approach to the subject). It is worth explaining, however, why most star formation results in a binary system, with one star rotating around the other. The lone Sun is, therefore, the exception rather than the rule.

Nuclear reactions provide the energy that makes a star shine. It then settles into a new stationary state. There is no further visible external change. Its radius remains the same and its energy output is practically constant. The first phase of its life, during which it contracts and warms up, takes about 15 million years. This phase is called *T Tauri*. The second phase, known as the *principal sequence*, during which it shines in a regular manner is presently that of our Sun and of 80% of the stars to be seen in the sky. It started 4.6 billion years ago for the Sun and will go on for another 5 billion years.

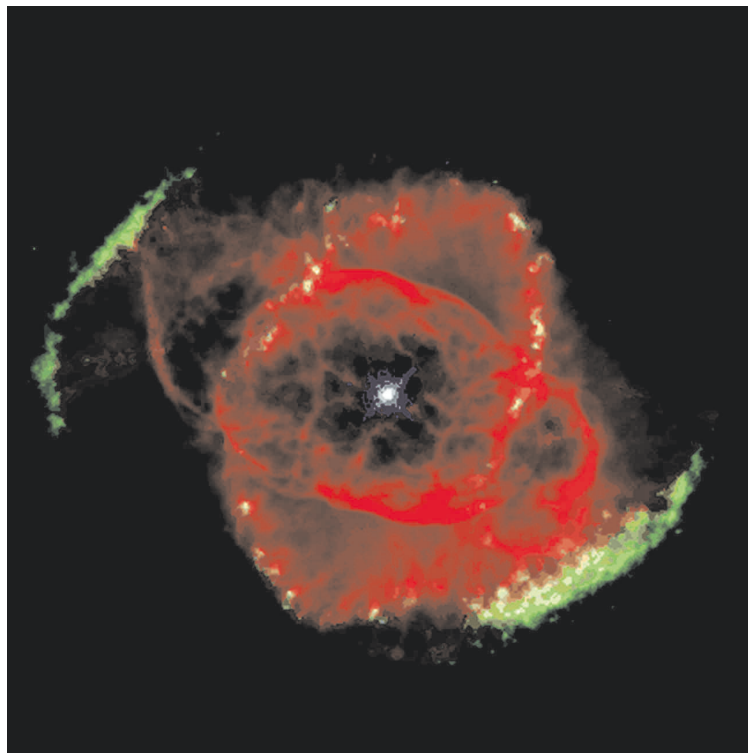
This nuclear phase comes to an end when the hydrogen in the stellar core has been consumed. The more massive a star, the more powerful its gravitational motor: it shines more brightly and its hydrogen reserves are used up more quickly. A star of ten solar masses consumes its fuel about 5,000 times faster than the Sun. However,

6 See appendix 2 for the two nuclear processes involved in this transformation.

7 At a temperature of 273.15 Kelvin and a pressure of 101,325 Pascal, one mole represents 22.4 liters of gas, i.e. 6.022×10^{23} molecules.

less massive stars have a life span equal to several times that of the Sun –that is, if they reach the principal phase, which is not the case for those with a mass of less than 0.07 of the solar mass. These "too small" stars contract into brown, then black, dwarfs or even, as is thought to have been observed in other systems, into giant planets.

In 5 billion years, when hydrogen accounts for only 5% of the core matter, the internal energy of the Sun provided by nuclear combustion will no longer be enough to offset the force of gravity that tends to make it collapse on itself. The contraction will then have the upper hand. When the core temperature exceeds 100 million degrees, a new nuclear reaction will become possible: three nuclei of helium will combine to form a nucleus of carbon. Before the start of this reaction, the increase in temperature brought about by the contraction will stimulate the nuclear combustion of the hydrogen round the circumference of the central area. This will lead to the dilatation of the star: the Sun will swell to factor 100 and will become a *red giant*, like Antares in Scorpion and Betelgeuse in Orion. Once the central



***Figure 1.3 - The NGC 6543 nebula, or cat's eye,
photographed by the WFPC2 on the Hubble space telescope***

Its complex shape suggests it comes from a system of double stars, one of which became a white dwarf, probably about a thousand years ago. The resolution of the telescope is not sufficient to make out the two stars (credit J.P. Harrington and K.J. Borkowski – University of Maryland; NASA).

combustion of helium has finished, the former convection zone of the star and a small amount of the matter produced by the nuclear fusion reactor –also known as *nucleosynthesis*– will be blown out into space, in the shape of a ring called a *planetary nebulous*, centered around a ball of hot ashes, a *white dwarf*, about the same size as Earth. This white dwarf will glow faintly before dying away to become a *black dwarf*, with a volume about a million times smaller than its present volume.

More massive stars, of about ten to twelve solar masses, are able to carry on the cycle, producing increasingly heavy elements, even iron. When they explode, they exist as supernovae for a few earth days, enabling even heavier atoms to be made and propelling all these elements into space. Therefore, all the matter that makes up telluric planets comes from one or more supernovae.

Inside the Sun itself, although the gas is made up essentially of hydrogen (93.96%) and helium (5.9190%) traces of other elements can also be found. Like telluric planets, they cannot be traced back to the primordial universe composed essentially of hydrogen and helium. This means that they too were produced by a star that has disappeared.

**Table 1.1 - The composition of the Sun
expressed in mass percentage of the various components⁸**

Name	Symbol	Mass %
Hydrogen	H	93.96
Helium	He	5.9190
Oxygen	O	0.0648
Carbon	C	0.0395
Nitrogen	N	0.0082
Silicon	Si	0.0042
Magnesium	Mg	0.0037
Neon	Ne	0.0035
Iron	Fe	0.0030
Sulfur	S	0.0015
Aluminum	Al	0.0003
Calcium	Ca	0.0002
Sodium	Na	0.0002
Nickel	Ni	0.0002
Argon	Ar	0.0001

⁸ These proportions were obtained by analyzing the solar spectrum, the composition of the solar wind and models of stars. Their accuracy during these calculations must not be misunderstood. Many questions remain unresolved; furthermore, the modifications inside the Sun are considerable. For instance, in the peripheral layers, the mass of hydrogen amounts to between 69% and 75%, that of helium to between 25% and 29% and that of other elements is around 2%.

The proportion of these elements in the Sun is so low that it could be considered negligible (table 1.1). However, it is of utmost importance for at least one reason: it enables the star to be characterized by observation. Each physical element has its own signature that depends on the wavelengths of the electromagnetic waves it emits at a given temperature. If we were able to observe only hydrogen and helium, the number of wavelengths would be limited, providing only part of the global information on the Sun. The fact that we can also observe the radiation of heavier elements such as oxygen, iron... provides a wealth of extra information.

Due to the high temperatures in all regions of the Sun, the elements mentioned above are dissociated into ions and free electrons. This type of mixture is called plasma. This is the fourth state of matter and can be solid (as with metals) or fluid. It can be mixed with neutral matter (this is the case with high altitude planetary atmospheres). It can be cold (as low as a few hundred thousand Kelvins) or hot (more than one million Kelvins). It is sensitive to the presence of an electromagnetic field and can generate one of its own.

2. THE CHARACTERISTICS OF THE SUN

The Sun is a star of average size, like billions of others in the universe. Here are its main characteristics.

Its equatorial diameter is 1,392,000 kilometers, that is, 109 times that of the Earth. Its mass of 2×10^{30} kilograms represents 99.97% of that of the solar system. Its density mass is $1,400 \text{ kg m}^{-3}$ —1.4 times that of water—about one quarter of that of Earth.

The Sun rotates on its axis. This axis is approximately perpendicular to the plane in which the Earth rotates round the Sun (the ecliptic plane) thus making it possible to define a geographical North Pole and South Pole. By agreement, these are on the same side of the ecliptic plane as the North and South poles of the Earth. Also by agreement, the solar East and West are opposite the terrestrial East and West for an observer placed between the Earth and the Sun.

Compared with those of the Earth, the rotation shows some surprising characteristics. To us, it seems perfectly natural for a day to have the same duration in the North or the South of France, Norway, Africa, at the bottom of the ocean or on top of a mountain. This is because the Earth rotates as a whole, rigidly. The same cannot be said of the Sun, where the speed of rotation of the surface matter near the equator is different from that found near the poles. Moreover, SOHO brought to light a gigantic flux of hot plasma, an equatorial "river" which flows 4% more quickly than the matter along its banks. This "river" is approximately 500,000 kilometers wide (Earth has a diameter of roughly 13,000 kilometers) and about 200,000 kilometers deep. Below the poles there are two other solar rivers which, although a great deal smaller than the equatorial river, are still huge by terrestrial standards: each of them is about 27,000 kilometers wide, enough to contain our planet twice over.

Table 1.2 - Some distinctive parameters of solar system planets and the Sun

	Diameter at the equator [km]	Mass [kg]	Mass / Mass of the Sun	Density in relation to liquid water	Specific rotation (day)	Gravity ^{**} [m s ⁻²]
Sun	1,392,000	2×10^{30}	1	1.4	25.38	275.5
Mercury	4,879	3.302×10^{23}	1.65×10^{-7}	5.43	58.65	2.78
Venus	12,104	4.870×10^{24}	2.44×10^{-6}	5.24	243.01*	8.60
Earth	12,756	5.974×10^{24}	2.99×10^{-6}	5.52	1	9.78
Mars	6,794	6.419×10^{23}	3.21×10^{-7}	3.93	1.026	3.72
Jupiter	142,984	1.900×10^{27}	0.95×10^{-3}	1.33	0.41	22.88
Saturn	120,536	5.685×10^{26}	2.84×10^{-4}	0.69	0.427	9.05
Uranus	51,118	8.683×10^{25}	4.34×10^{-5}	1.27	0.45*	7.77
Neptune	49,528	1.024×10^{26}	0.51×10^{-4}	1.64	0.67	11
Pluto	2,390	1.238×10^{22}	0.65×10^{-8}	1.73	6.39	0.4

* The rotation of Venus and Uranus is retrograde, i.e. in the opposite direction to that of the Earth.

** Mean gravity on the surface.

As the Sun rotates, the matter at the equator drifts towards the poles at a relatively slow speed: about 80 kilometers per hour. The flow of matter back from the poles towards the equator theoretically occurs at a depth of approximately 200,000 kilometers (this has not yet been confirmed) meaning the matter is transported roughly ten times more slowly than on the surface. It would, therefore, take more than twenty years for a particle to complete the full cycle from the surface of the solar equator to a pole and then back through the inside of the Sun; this value can be compared with that of the duration of the cycle of solar activity.

Since the speed of rotation of the Sun varies between the equator and the pole, the latitude⁹ must be specified each time a value is given. The usual reference is 16°. At this latitude, as seen from the Earth, the Sun appears to complete a rotation in 27.2753 terrestrial days. If we take a latitudinal average from the equator to the pole, we obtain a value of 27.7 days with extreme values of about 35 days near the poles and 25 on the equator. This is known as *synodic rotation*. However, the Earth rotates on its axis as well as around the Sun. The solar rotation we can observe from

⁹ The latitude of a site on a rotating sphere is the angle between the zenith of the site and the equatorial plane. This notion will be brought up again in chapter 2 and its appendixes.

Earth is, in fact, a combination of terrestrial rotations and the specific rotation of the Sun. An observer at a fixed point in the solar system would only see the rotation of the Sun itself i.e. *sidereal rotation*, which is, on average, 25.38 days over a given time, at said latitude of 16° .

We have presented an account of the speed of rotation on the surface of the Sun. However, just as this varies with latitude, it also varies with depth. Based on indirect measurements, going down into the Sun, the synodic rotation speed (which will be used for future reference and which is 27.7 days on average) first increases down to a depth of 50,000 kilometers from the surface, where the rotation takes 26.6 days. It then decreases steadily according to depth down to 0.5 of the solar radius (rotation in about 29 days). However, the core of the Sun rotates on its axis in about 8 days.

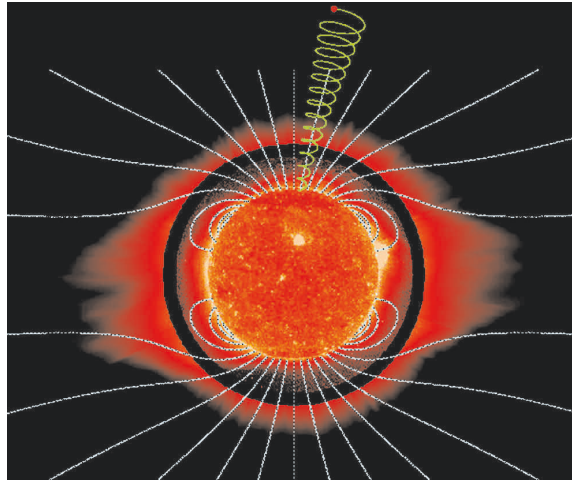
The mean value of the magnetic field¹⁰ on the surface of the quiet Sun –this expression will be explained shortly– is about 10^{-4} Tesla¹¹. In the direction of the Earth from which we observe it, the component of this field is known as the *longitudinal* component. It is also roughly equal to one Gauss. Our Earth also has a magnetic field equal to about 0.5 Gauss on its surface, i.e. comparable to that of the Sun. On our planet, we are accustomed to our two magnetic poles, the North Pole and the South Pole. A magnetic field which has two poles is said to be dipolar. However, can the same be said of the Sun? The answer is yes, but in a strange manner: the dipolar component of the Sun varies in intensity in time and this variation appears to be relatively cyclical, over a period of eleven years.

In addition to this dipolar component, there are two extra pairs of North and South poles, as shown in figure 1.4; obviously this form is said to be quadrupolar and is also variable in time. However, whatever the scale, the magnetic field of the Sun contains components that make it extremely complex to describe. Figure 1.5 represents a model that reproduces observations of the magnetic field on the surface of the Sun.

For a few years now, it has appeared that the Sun's behavior could be interpreted and predicted if we had precise knowledge of its magnetic field, down to its most intimate scales. However, we are still a long way from having acquired this knowledge.

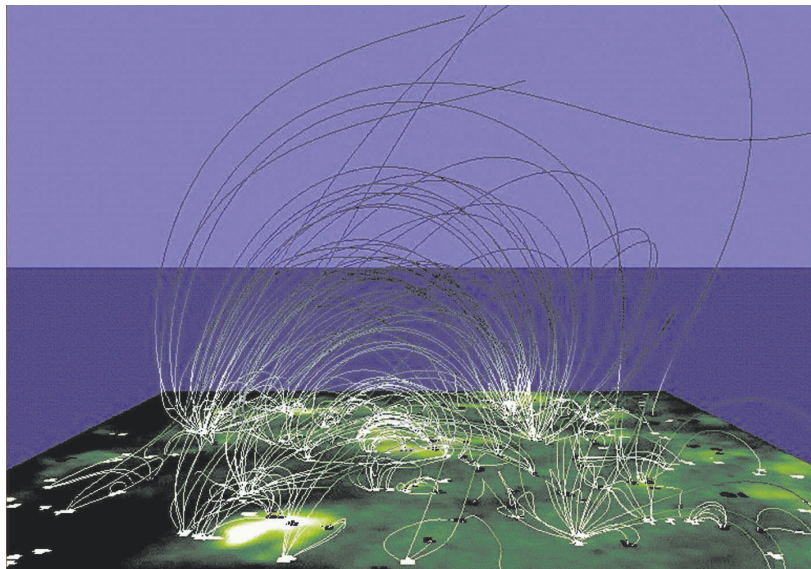
10 A magnetic field is associated with charges in motion. When a charge undergoes a rotating movement, its magnetic moment is perpendicular to the rotation plane. Generally, magnetic moments are distributed at random throughout matter so that the resultant (the sum of the moments) is zero. When the movements become organized, the magnetic moments can add up so that the resultant is not zero. Electromagnetism and in particular the expression of the dipole are revised in appendixes 3 and 4.

11 10^{-4} Tesla = 1 Gauss.



**Figure 1.4 - Solar magnetic field lines,
generated by a theoretical model for minimum solar activity**

Here we see a dipolar component (i.e. a North pole and a South pole) and also quadrupolar components. The coronal holes (see this chapter) are surmounted by open lines on which solar particles spiral. This set of pictures shows the ultraviolet solar radiation emitted by the corona (see this chapter) on August 17 1966. The photograph of the solar disk (also in this chapter) was taken by the EIT instrument and that of the corona by the UVCS instrument (in a five-times ionized oxygen wavelength). Both instruments were on board SOHO.



**Figure 1.5 - Small-scale solar magnetic field lines
as shown by a theoretical model and observations**

Here the highest lines are at approximately 0.25 solar radii. The horizontal scale is on the order of 100,000 kilometers (credit SOHO/MDI).

3. A REPRESENTATION OF THE SUN

We can understand what goes on in the Sun's interior, by comparing it with water boiling in a saucepan. The flame of the stove represents the core of the Sun. However, whereas in the saucepan the energy is produced by a chemical reaction between the gas on the stove and air, inside the Sun it is produced by nuclear fusion.

The saucepan does not distort upon heating. It simply transmits energy by radiation and is a radiative zone. In the same fashion, around the core of the Sun, matter is not compact enough to generate a nuclear fusion, yet it is too compact to move. It can only radiate the energy it receives.

When boiling occurs in the saucepan, the heated water at the bottom rises to the surface, cools as it rises and sinks to the bottom again; this is known as convection. In a broader sense, certain types of heaters that create atmospheric convection are called convectors. Likewise, on the Sun, moving from the core to the outer layer, gravity is no longer sufficient to compact the matter: boiling can take place and we have the solar convection zone that corresponds to matter set in motion by convection.

Moreover, just as evaporation takes place above the saucepan, there is also a phenomenon of solar evaporation. If we look closely, we can see that droplets of water are ejected between the convection bubbles of water. On the Sun, matter is ejected from the surface.

However, the comparison must not be taken too far: to begin with, the production of energy is of a different nature (nuclear fusion as opposed to the combustion of a gas). Next, the atoms that make up the saucepan are bound together by electrostatic forces, not gravitational forces. The water is inside the saucepan whereas the solar radiative zone is inside the convection zone. Solar evaporation is not the same as that of a liquid and magnetic forces also contribute to the ejection of droplets of solar matter.

This type of representation of the Sun was first acquired in the 1950s and hardly changed at all over the next 40 years. More recently however, our vision has progressed somewhat.

4. THE INTERNAL STRUCTURE OF THE SUN

In the heart of the Sun, the nuclear oven occupies a sphere with a radius of 200,000 kilometers, where 50 to 70% of the total mass of the star is concentrated. We have already seen that hydrogen is changed into helium by nuclear fusion. Along with these reactions there is a loss of mass due to an emission of energy according to the well-known formula $E = mc^2$, in which E is the energy produced by

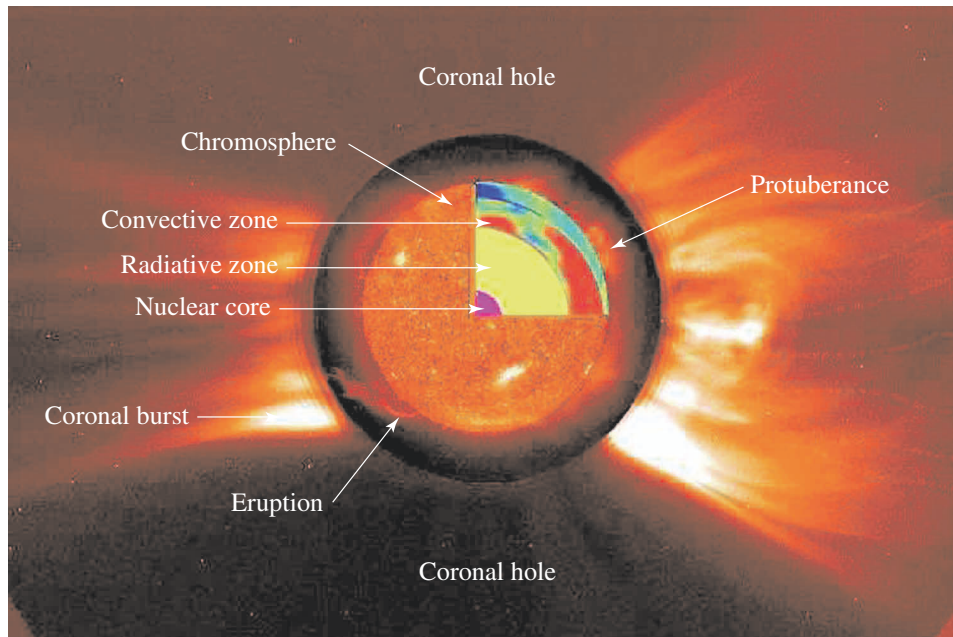


Figure 1.6 - The structure of the Sun as given by various instruments on board the SOHO satellite (sources SOHO/MDI for the internal section, EIT for the chromosphere, LASCO for the solar corona)

a mass m and c is the speed of light in a vacuum¹². Every second, 700 billion kilograms of hydrogen fuse into 695.7 billions of kilograms of helium. Most of the energy (98%) is evacuated in the form of photons¹³.

In the center of the Sun, the concentration amounts to 5×10^{31} particles per m^3 (compared with that of the terrestrial atmosphere at ground level which is about 10^{25} particles per m^3). The voluminal mass is 150 tons per m^3 , pressure is about 220 billion times atmospheric pressure and the temperature about 15.6 million degrees. The Sun began its nuclear combustion about 4.6 billion years ago. The core is therefore already hydrogen-depleted and it is estimated that the maximum level of the present source of energy production is located at approximately 0.1 solar radius from the center.

How can we be so sure of all this without being able to see it with our own eyes? Experimental and numerical models have shown that apart from nuclear fusion no known source is capable of producing the energy that the Sun produces. By measuring

¹² $c = 299,792,458 \text{ m s}^{-1}$; this is generally rounded off to $3 \times 10^8 \text{ m s}^{-1}$.

¹³ The photon is a small quantity of luminous energy. For a light of frequency ν (in Hertz) energy E (in Joule) of the photon is obtained by $E = h\nu$ where h is the Planck constant ($= 6,626 \times 10^{-34} \text{ J s}$).

the quantity of light released by the Sun, we can estimate the amount of matter required to produce it. The analysis of the light and of the composition of interstellar space, gives us the composition of the Sun and, therefore, the mass of its core.

The remaining 2% of solar energy are evacuated in the form of particles known as neutrinos which probably have no mass¹⁴.

The energy produced in the nuclear oven has to go through various layers before travelling through space. The first of these, the *radiative zone*, covers about 0.3 to 0.7 solar radii. The concentration decreases from 1.4×10^{31} to 1.7×10^{28} particles per m^3 between its internal surface (near the core of the Sun) and its external surface. The rotation of this zone is probably rigid, i.e. it turns as a single block¹⁵. Between one half to one third of the Sun's total mass is contained in this radiative zone, with the pressure decreasing from approximately 30 million atmospheres in the center to 6 million on the outside and a temperature that drops from 8 to 1.3 million degrees. Like the following zones, it is transparent to the neutrinos which pass through it in about 2 seconds. However, the energy transported by the photons takes several million years to leave the zone: some photons are absorbed, others are re-emitted¹⁶ a great many times resulting in a widening of their spectral line.

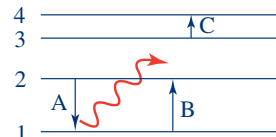
**Table 1.3 - A comparison of some solar parameters
from the heart to the photosphere**

	Concentration [m^{-3}]	Pressure [atm]	Temperature [°C]	Depth [km]
Center	5×10^{31}	220×10^9	15.6×10^6	– 700,000
Radiative zone / heart interface	1.4×10^{31}	30×10^9	8×10^6	– 500,000
Convective zone / radiative zone interface	1.7×10^{28}	6×10^6	1.3×10^6	– 200,000
Photosphere	6.6×10^{19}	0.12	6,000	0
Terrestrial atmosphere at sea level	10^{25}	1	15	0

14 Up to about year 2000, the neutrinos observed seemed in excess compared to what the theory predicted. A recent explanation is that the three types of neutrino may oscillate between themselves; this would account for the difference observed.

15 Here again, measurement is indirect. We have access to the deformations of the Sun caused by rotation, from which it can be deduced that a radiative zone in non-rigid rotation would not be compatible with the observations.

16 If we schematize electron energy levels on a very elementary little diagram as shown below, when electron A jumps from level 2 (energy E_2) to level 1 (energy E_1) this creates a quantum of energy, a photon of energy E that corresponds to a light of frequency ν so that $E = E_2 - E_1 = h\nu$. However, electron jumps B and C require an external source of energy, for instance, that of photons. In the case of the figure, the energy of the photon absorbed in jump B is higher than that absorbed in jump C.



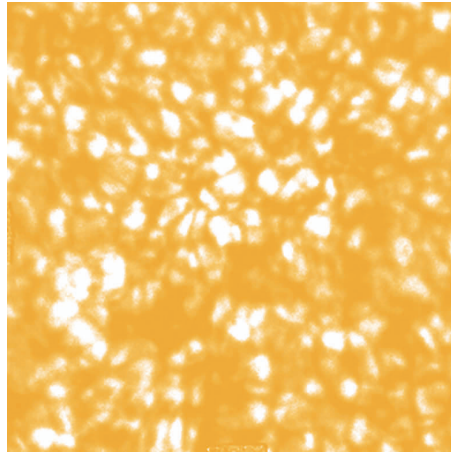


Figure 1.7 - This picture of solar granulation was taken on June 20 1999, with THEMIS (Heliographic Telescope for the Study of Solar Magnetism and Instabilities) one of the very large CNRS instruments, developed in collaboration with Italy
*It represents a square with sides of approximately 24,000 kilometers.
 (credit THEMIS/CNRS/INSU/CNR)*

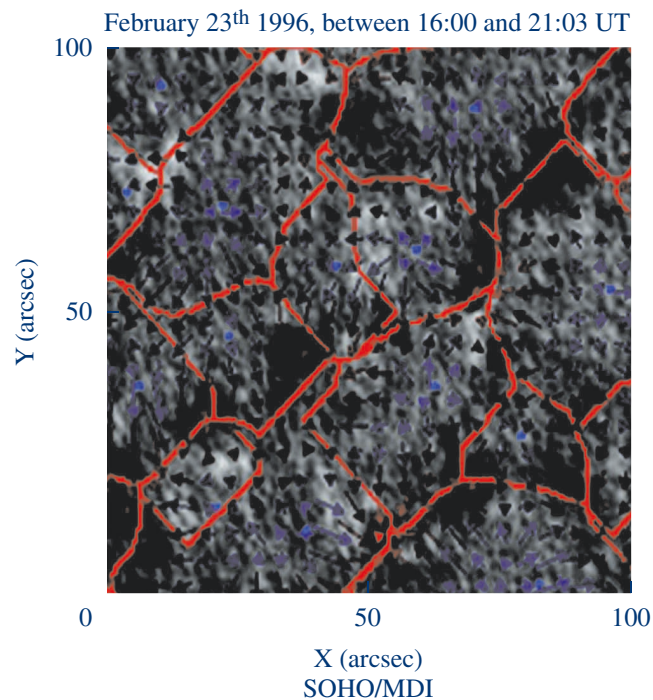


Figure 1.8 - A supergranulation network superimposed in red on a photograph taken by the MDI instrument on SOHO
The arrows represent the speed of ascension of the supergranules, with the blue to the top. Each side of the picture represents approximately 120,000 kilometers.

At the end of this long journey, the photons reach an agitated zone, the *convection zone*, in which protons and electrons spin round and round and form cells. The convection corresponds to a bulk motion of matter: hot gas rises, then cools, transmitting energy to the superficial layers of the solar atmosphere before sinking down again. In the outer region of the convection zone, on the surface of the Sun, the temperature is only about 6,000 degrees. Although this motion does not occur in a perfectly coherent manner, observation has shown a cyclic variation of 5 minutes for the vertical speeds (this has given rise to a branch of astrophysics called solar seismology). From the Earth, these cells resemble grains of rice and are therefore known as *granules*. The average diameter of a granule is 1,200 kilometers and the distance between the center of the granules is, on average, 1,500 kilometers. So they are huge bubbles of soup rising and sinking on the surface of the Sun! The duration of a granule is 18 minutes on average and it rises to an altitude of about 200 kilometers. There are several states of convection. *Supergranules* are of the same origin and aspect as granules but differ in size (30,000 kilometers), speed of ascension (360 kilometers per hour) and duration (20 hours). They too are triggered by the convection of hot matter but in this case from deeper layers as in the saucepan where bubbles of different sizes can rise to the surface.

How can we see these solar bubbles? One method is to observe only what moves i.e. by taking snapshots one second apart and screening them dot by dot. If there has been no motion, the difference between the pictures will be completely black. Any part that is not black corresponds to a movement. The Doppler effect¹⁷ is then used to interpret the results. A rising supergranule corresponds to a decrease in the wavelength of the light wave received. For the observer, the color shifts toward blue. When the supergranule falls back down, the wavelength of the light wave received increases and the color shifts toward red. By studying the differences between frames it is possible to tell not only what has moved but also the direction of movement relative to the observer.

The photograph of the Sun in figure 1.9 is based on this principle. First of all, it shows that the Sun rotates on its own axis. The left side is moving toward the observer while the right side is drawing away, giving the attractive graduated shading. This mean rotation then has to be screened and the picture re-processed to highlight its main characteristics. The result can be seen in figure 1.10.

17 The velocity v of displacement of a body that emits a light of wavelength λ can be calculated by the difference $\Delta\lambda$ between the wavelength of the light observed and that of the light emitted. The relation is: $v = c \frac{\Delta\lambda}{\lambda} = c \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$. In this convention, v is positive when the body at the source of the light is moving away from the observer. A demonstration of the former formula can be found in appendix 5.

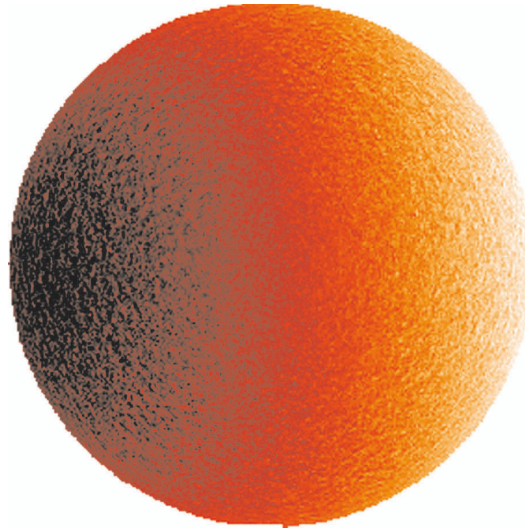


Figure 1.9 - This photograph of the Sun was taken by the MDI instrument on board SOHO on March 30 1996

MDI uses the Doppler effect. The darkest shades correspond to a movement of 2,500 metres per second towards the observer and the white to a movement of 2,000 metres per second away (credit Stanford Loockheed Institute for Space Research; SOHO/MDI).

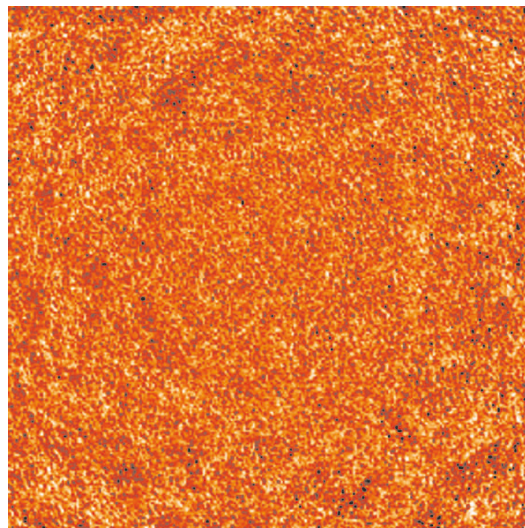


Figure 1.10 - Part of the Sun after processing picture 1.9

Here the darkest shades correspond to a movement of 50 meters per second towards the observer and the lightest to a movement of 50 meters per second away (credit SOHO/MDI).

When processed, the picture reveals bubbles of different sizes: they are granules or supergranules. By studying a great many exposures of this type, it was shown as early as 1960 that granules appear and disappear with a periodicity of 296 seconds (with an uncertainty of ± 3 seconds). It was very quickly assumed that the origin of the phenomenon was to be found inside our star, providing an indirect way of studying the Sun's interior.

Radiative and convection zones can be differentiated by their dynamics. The rotation of the former is rigid, solely zonal and its speed which is perpendicular to the axis of rotation of the Sun, is probably slower (about 29 days) than that of fluid rotation. At the interface between the two zones, charged particles trigger friction and this creates currents known as "dynamo" currents. It is estimated that these electric currents are at the origin of the large-scale solar magnetic field (at least as far as dipolar and quadrupolar components are concerned). The flow of matter from the equator towards the poles on the surface and from the poles towards the equator in the depths of the Sun, very likely contributes to the formation of the magnetic field and its variations in time.

Astronomy, like all other fields of science, progressed considerably during the 20th century. What did we know about the Sun a hundred years ago? Since we had no knowledge of nuclear physics, its energy was thought to be generated solely by the collision of condensed matter.

"On the assumption that nebulous matter was, at the start, extremely tenuous, a calculation was made of the amount of heat that could have been generated by all these molecules falling toward the center, by the condensation that was at the origin of the solar system. Assuming the specific heat of the condensing mass to be that of water, the heat from the condensation alone would have been enough to produce a rise in temperature of 28 million degrees centigrade (...). The condensation movement was more than sufficient to produce the present temperature of the Sun and the temperature originating from all the planets (...). If the rate of emission remains at the present level, the solar heat produced by the former condensation of its mass will last for approximately 20 million years."

(C. FLAMMARION, *Popular Astronomy*, 1882)

5. THE PHOTOSPHERE, SOLAR RADIATION, THE SOLAR WIND

The *photosphere* is the visible "surface" of the Sun. It deserves a special mention in the description of our star insofar as this is where most of the radiation and the solar wind come from. It is a definite boundary since it is the seat of the granules, supergranules and other phenomena such as sunspots or filaments covered in this chapter.

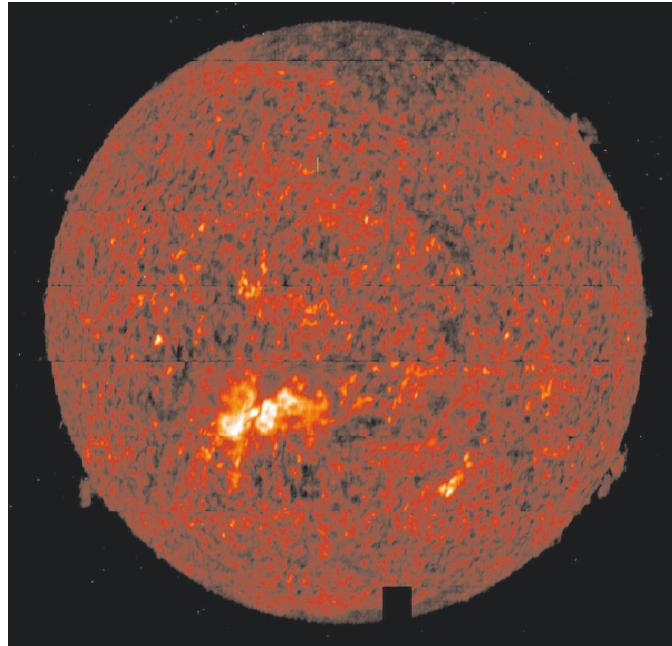


Figure 1.11 - A picture of the photosphere taken with a filter letting through light with a wavelength of 58.4 nanometers (neutral hydrogen lines) on August 28, 1996
An assembly of 11 hours of observation at high resolution (credit CDS/SOHO).

99% of the total radiation is given off by the photosphere. The energy given out is approximately 4×10^{26} Watts (about 260 million Watts per square meter of solar surface). The Earth receives only 1.743×10^{17} Watts at cloud level or 1366.1 Watts per square meter over the area of its surface lit by the Sun at the zenith. The latter number is also called the *solar constant*, in spite of the fact that it is probably less constant than was thought only a few years ago.

Its radiation spectrum is similar to that of a blackbody¹⁸ at 5,777 Kelvins. A blackbody is a thermodynamic system that radiates at its own equilibrium temperature. The properties of a blackbody, of its spectrum in particular, depend only on the temperature: the total amount of energy emitted over the whole spectrum per unit of area (luminous flux density) varies as the fourth power of the temperature. The constant of proportionality is called the Stefan constant and is equal to $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$. In other words, if we compare a fireback to a blackbody, the higher its temperature rises, the more it radiates towards the room it is heating.

The spectrum of the blackbody can be calculated using a formulation expressed by PLANCK in 1901. In figure 1.12 the blue line represents the spectrum of a blackbody at 5,777 Kelvin and the red line the measured spectrum of the Sun. The differences

¹⁸ Appendix 6 contains a presentation of the photometric magnitudes and appendix 7 describes the black body and the most commonly used relations (laws of Wien, Stefan, Planck).

are due in part to the absorption of lines in the media traversed between the photosphere and the point of observation, but also to the fact that the blackbody radiation requires thermodynamic equilibrium, which is not quite achieved on the Sun. However, the differences remain slight.

The principal characteristic of the visible radiation of the Sun is its stability. Its analysis shows that it spans all colors¹⁹. However, some of the wavelengths emitted by the photosphere are absorbed in the atmosphere of the Sun and it is possible, in a solar spectrum, to distinguish between the lines emitted and the lines absorbed (known as the emission or absorption spectrum). Figure 1.13 shows the range of colors of the visible solar radiation.

When PLANCK put forward a theory in 1901, little did he suspect the presence of such intense invisible solar radiation²⁰. In 1937, SAHA demonstrated that the excitation of atmospheric nitrogen could only be explained by the presence of photon radiation far more energetic than that which could be observed and at least a

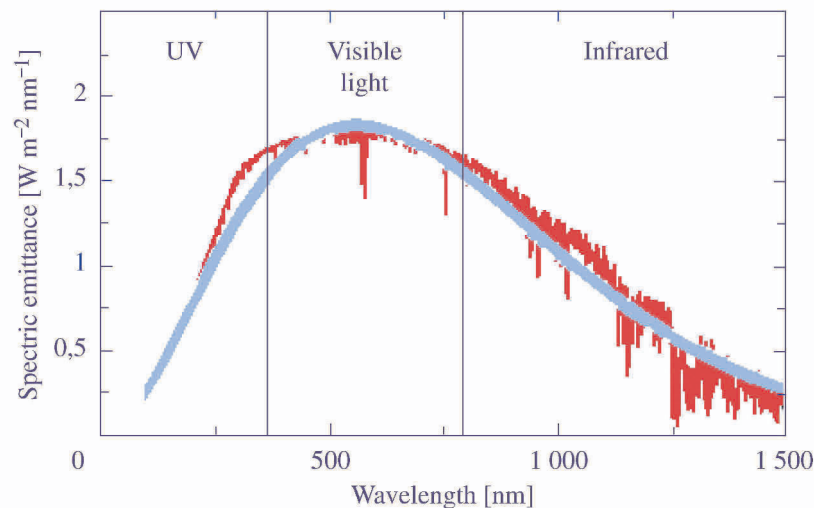


Figure 1.12 - A comparison between the spectrum of the black body at 5,777 Kelvin (blue curve) and the solar spectrum (red curve)



Figure 1.13 - The solar spectrum obtained in 1972 on top of the Jungfrau at 3,600 metres

The abscissa runs from 300 nanometers (on the left) to 1,000 nanometers (on the right) (credit L. Delbouille, L. Neven, G. Roland, BASS 2000).

¹⁹ The spectroscope, with which several of the lines of the solar spectrum were dissociated, was invented by FRAUNHOFER (1787-1826).

²⁰ Appendix 8 contains a presentation of radiation scales.

million times more considerable than predicted by PLANCK. It was not until 1946 that the first experiments carried out from rockets made it possible to measure effectively the short wavelengths of solar radiation: ultraviolet (UV), then X-rays and, finally, gamma rays, the latter being the product of radioactive disintegration. The major characteristic of UV and X-rays is that they vary tremendously from one hour to the next, one month to the next and one year to the next. The ultraviolet flux can be multiplied by two and the X flux by thirty. Ultraviolet is more abundant but unfortunately the instruments used to measure its spectrum are heavy and, therefore, difficult to take on board a satellite.

The photosphere is not only the principal site in space from where electromagnetic waves are emitted, it is also the area where particles that make up what is known as solar wind are emitted. This phenomenon is closely related to the presence of a solar magnetic field. We have pointed out that the magnetic field has large-scale components, the origin of which can probably be found at the interface between the convection zone and the radiative zone (see figure 1.4). The magnetic proliferation on the surface of the Sun (see figure 1.5) is probably due to the convection of ionized matter that creates numerous local magnetic fields. However, just as charged particles in motion create a magnetic field in a symmetrical pattern, a magnetic field draws the electrically charged particles along its field lines²¹.

Now, let us imagine the convection of plasma that creates a local magnetic field on the Sun, with a local North pole and a local South pole. These poles are linked by field lines, around which plasma travels. Furthermore, due to the bubbling effect of the photosphere an ejection of plasma towards the outer region of the Sun at speeds of between 700,000 and 2.5 million kilometers per hour is added to the movement along the field lines. To use a vivid image, the magnetic field lines carried by the plasma stretch toward the outer region of the Sun, into interplanetary space, while keeping their feet on the Sun.

Once it has left the Sun, this field is called "interplanetary" and the plasma becomes known as "solar wind". In the case of the Sun, it is impossible to say whether the field generates the movement of plasma or vice-versa. They are said to be "frozen" within each other²² or that we have a frozen flux situation. This is what an observer on the Sun would see. An observer placed outside the star would have to add to the movement of particles the specific rotation of the Sun, and especially the fact that the footpoints of the field lines are anchored to the sun itself. The effect resembles water spraying out of a portable watering-can: an ant on the watering-can sees the

21 A magnetic field line is the curve that is tangential at all points to the local magnetic field. Like the equator or the isobars of a meteorological map, a field line is an imaginary line but can be used as a guide for physical representation (see appendixes 3 and 4).

22 In relation to the equations of appendix 9 concerning electromagnetism, this results in stationary electromagnetic forces i.e. $q\vec{E} + q\vec{v} \wedge \vec{B} = 0$ where $\vec{E}$ is the electrical field vector, $\vec{B}$ the magnetic field vector and $\vec{v}$ the velocity of the particle of charge q .

water spray straight out (radially) but the gardener sees a spiral known as the "spiral of Archimedes" Seen from the Earth, the interplanetary magnetic field does not appear to arrive in a straight line from the Sun but rather from its western limb (which also corresponds to the western edge of Earth for an observer on the diurnal side) From this point, for the same observer, it hits the spatial environment in a graceful east-west curve (figure 1.14).

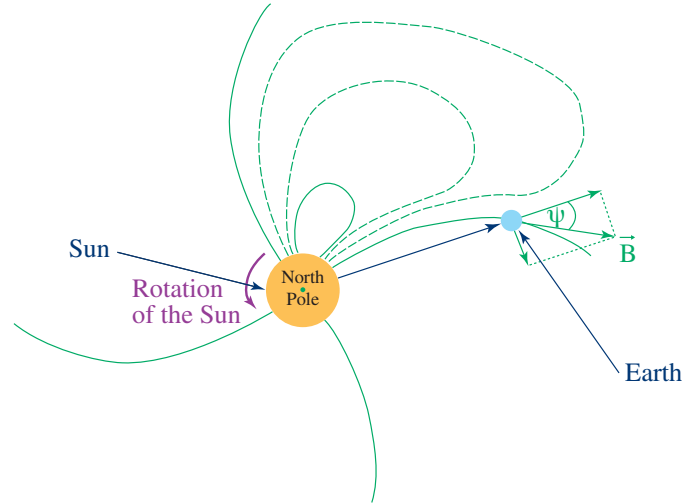


Figure 1.14 - Archimedes spiral

The lines represent the interplanetary magnetic field or the trajectory of the frozen solar plasma, indiscriminately.

The angle Ψ formed by a field line and the radial axis (with the Sun as the starting point) at a given spot depends on the ejection velocity of the solar wind. At Earth level, it is roughly one radian (or about 60°) for a mean wind velocity of 370 km s^{-1} . By then, the particles have covered a distance of 1.4 AU ²³ along this path.

We have just described a first process of particle exchange between the surface of the Sun and its atmosphere. This emission is permanent and concerns the greater part of the photosphere, the solar zone known as "quiet". The energy given out during

23 At terrestrial orbit level, angle Ψ between the spiral of Archimedes and the axis connecting the Sun to Earth, measured on the nocturnal side, is expressed in function of speed V (km s^{-1}) of the solar wind stream according to: $\Psi = \frac{23\,150}{V}$ if Ψ is expressed in degrees and $\Psi = \frac{404}{V}$ when expressed in radians.

Length L (in astronomical units) of the magnetic field line connecting the Earth to the photosphere is then: $L = \frac{1}{2} \left(\sqrt{\Psi^2 + 1} + \frac{\text{Ln}\Psi + \sqrt{\Psi^2 + 1}}{\Psi} \right)$ where Ψ is expressed in radians.

For a mean wind of 370 km s^{-1} , the angle obtained is 62.6° ($\approx 1 \text{ rd}$) and length $L \approx 1.4 \text{ UA}$.

Table 1.4 - Solar wind parameters at 1 AU

	Usual high values	Minimum observed	Nominal value
Number of particles per m ³	83×10^6	≈ 0	5×10^6
Velocity [km s ⁻¹]	950	250	370
Total intensity of the interplanetary magnetic field [nT]	85	≈ 0	6
Intensity of the North-South component of the interplanetary magnetic field [nT]	27	- 31	0

the ejection of these particles is roughly 10,000 Watts per square meter of solar area, which may seem low in comparison with the energy radiated as light. However, the influence of this solar wind has revealed itself to be of the utmost importance in space weather.

The mean concentration of solar wind at Earth level is 5 million particles per square meter i.e. roughly 5×10^9 times lower than that of the air we breathe. The temperature ranges from a few hundred thousand to a few million degrees. However, here the notion of temperature has a completely different meaning. Air temperature, for instance, is the result of thermal exchanges caused by collisions between particles. When we receive heat from the air it is due to the collision of various molecules on our skin. In other words, temperature is a statistical quantity, a mean value taken from an infinite number of impacts.

There seems to be no point in measuring the temperature of a single particle since, alone, it cannot exchange heat. This is more or less what happens in the solar wind. There are relatively few particles and since they are all moving in the same direction the likelihood of them coming into contact is very low. On average, over the 200 million kilometers separating the Sun from the Earth (taking into account the spiral of Archimedes) they have less than ... 5 chances of collision! By temperature, therefore, we mean the correspondence of particles in speed: the hotter they are, the faster they are, or, in other words, the more energetic in terms of kinetic energy²⁴.

Up until 1995, the only data concerning solar wind came from measurements taken along the rotational orbit of the Earth, i.e. at one Astronomical Unit and in the

24 For a gas at temperature T, statistic mechanics give the expression of kinetic energy E_c in

$$\text{function of mass } m \text{ of a molecule and its mean quadratic velocity } E_c = \frac{N_{ddl}}{2} k_B T = \frac{1}{2} m \overline{v^2}$$

– N_{ddl} is the number of degrees of freedom of the gas. In the terrestrial atmosphere, for neutral particles, it is equal to 3 since the gas can move freely in three directions (gravity is not taken into account). In the solar atmosphere, it can be considered that magnetic stresses reduce the number of degrees of freedom to 2, so that $E_c = k_B T = \frac{1}{2} m \overline{v^2}$.

ecliptic plane. Since then, our knowledge has been enriched by the data obtained by the ULYSSES probe which measures solar wind pole to pole at about 1.3 AU from the Sun. Before this, there were two contradictory models of solar wind, both based on observations made in the ecliptic plane. The first model predicted a gradual increase in solar wind velocity from the solar equator to the poles while the other suggested that velocity would be maximum at a mean latitude. Neither of these models was proven to be correct: during its first orbit, which took place in quiet solar conditions, ULYSSES observed that there are two distinct types of solar wind. Between the heliospherical latitudes²⁵ of 20° North and 20° South (thus comprising the ecliptic plane) the solar wind flows at an average speed of 400 kilometers per second (this value can vary considerably). Then, over a distance of fewer than ten degrees, it increases to 750 kilometers per second. The regime then becomes fast but noticeably less perturbed. The speed then increases slowly to reach approximately 800 kilometers per second at latitude of about 80°. During its second orbit, which took place during active conditions, the picture was much more disturbed. The reason will show up clearly later.

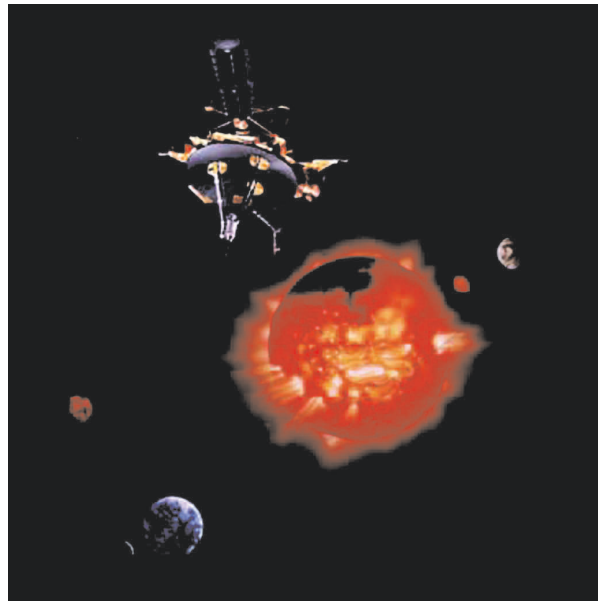


Figure 1.15 - An artist's impression of the ULYSSES satellite orbiting round the Sun, beyond the orbit of the Earth that can be seen in the foreground
The scales between the Sun and the planets have not been respected.
(credit ULYSSES/ESA/NASA)

25 Concerning the solar sphere. The heliosphere is the area in space that undergoes the influence of the solar atmosphere; it reaches as far as the limit where the stellar wind from other stars clashes with the solar wind (between 100 and 150 AU).

The models predicted a decrease in the flow of the solar wind above the poles. This is not so. Although there is a considerable decrease in the density of the solar wind, it is, on average, less considerable than the increase in velocity, resulting in a slight increase in the flow rather than the expected decrease.

6. THE THERMAL PROFILE OF THE SOLAR ATMOSPHERE

Beyond the photosphere is the beginning of the solar atmosphere which, for a long time, could only be observed from the Earth's surface in white light, during eclipses. Observations of this type are limited by the natural opacity of the atmosphere of our planet. Furthermore, details only become visible when their brilliancy differs from the natural background. This is the case when there is a significant difference in concentration or in temperature between a structure of the Sun and its environment. Right up to the 1990s, our description of the Sun was misled by our senses: we were unable to see the evolution of these structures, as they passed through zones of solar atmosphere with different macroscopic characteristics and therefore with brilliancies that moved through space and sometimes disappeared. To study the atmosphere of the Sun, it is essential to start by defining the thermal profile of its surface on the corona.

Our knowledge is largely based on the following observational principle: when atoms receive heat, the thermal energy can exceed the electromagnetic energy that maintains the electrons in a given situation in relation to their atomic core. An electron is released and the atom is ionized. The higher the temperature rises, the more the ions thus created lose their electronic shell. As the temperature rises, atoms with several electrons will be transformed into increasingly (positively) charged ions. Iron that has been ionized up to fifteen times can be found on the Sun. When particles are excited, they are de-excited by emission of radiation with a specific wavelength, a kind of signature. The idea, therefore, is to observe the Sun at specific wavelengths to highlight specific ions and, consequently, the temperature of the medium.

The temperature is not the same throughout the photosphere. Moving spaceward, it drops by about 1,000 degrees over a layer of about 500 kilometers (this varies with the granular movements). Like our ejections of boiling water, solar matter is propelled permanently between granules and supergranules in the form of proton and electron tongues known as *spicules* (between granules) or *macrospicules* (between supergranules). The main characteristics of spicules are a base diameter of 1,000 kilometers, a height of between 5,000 and 10,000 kilometers, a mean number of 30 per super-granule and a lifespan of 8 minutes. Their temperature is about 100,000 degrees. Although their correlation with the magnetic field has been proven, their origin is still uncertain.

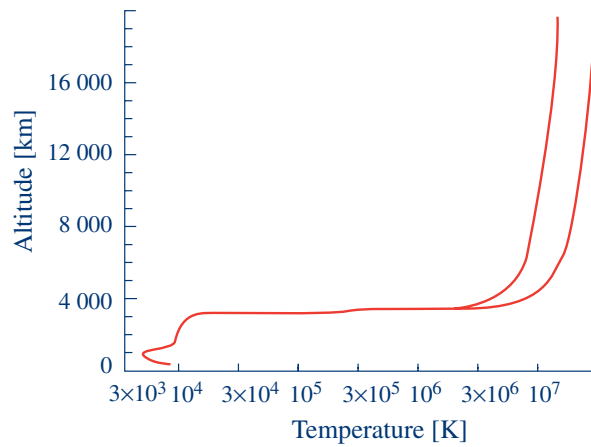


Figure 1.16 - Thermal sections of the solar corona

The two curves correspond to a quiet Sun (lowest temperatures) and to measurements that include emission from the active regions (highest temperatures). Altitude zero corresponds to the top of the convection zone (according to G.W. Simon and co-authors, *Solar Physics*, volume 39, 1974).

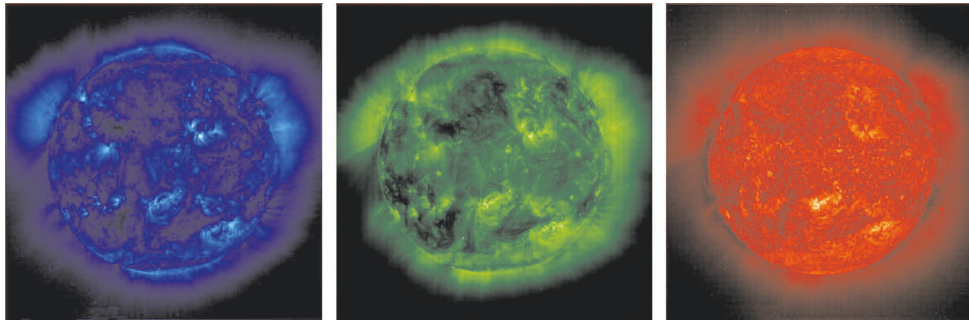


Figure 1.17 - The Sun photographed by EIT on board SOHO

In blue, the picture taken at 17.1 nanometers on August 11th 1999. This radiation is emitted by eight or nine times ionized iron and at a temperature of about 1 million degrees. In green, on the same day, radiation emitted by eleven times ionized iron at 1.5 million degrees, wavelength 19.5 nanometers. Lastly, in brown, radiation of fourteen times ionized iron at 28.4 nanometers. Photograph taken on February 3rd 1996. The temperature is as high as 2 to 2.5 million degrees (credit SOHO/EIT).

Just above the photosphere, forming a layer of about 1,500 kilometers, is the *chromosphere*²⁶, where there is an increase in temperature. Over this short distance, the electrons gain 6,000 degrees (the temperature increases from 6,000 to

²⁶ During an eclipse of the Sun, a thin fringe appears; it is red in color, (due primarily to the H α emission of hydrogen at 656.3 nanometers). This colored appearance explains why it is known as the chromosphere.

12,000 degrees) that is a gain of about 4 degrees per kilometer. The source of heat is, of course, photospheric radiation but, also, a magnetic interaction, which has not yet been correctly modeled. The spicules that rise to an altitude of several thousand kilometers pass through the chromosphere. Other horizontal structures called *fibrilles* carry matter. These are relatively cold, dark structures of matter that appear to define the limits of the magnetic structures of the chromosphere. Spicules, macrospicules and fibrilles form networks and, in altitude, these networks reproduce the granules and supergranules of the photosphere.

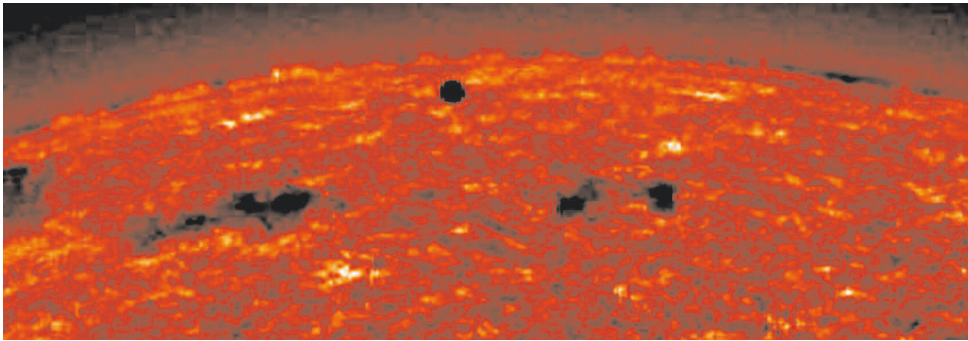


Figure 1.18 - On November 15th 1999, it is Mercury's turn to try and eclipse the Sun
The TRACE satellite photographs the event. On the edge of the solar corona, spicules i.e. tongues of fire can be seen rising from the photosphere (credit Big Bear Laboratory (BBSO – California); New Jersey Institute of Technology (NJIT)).

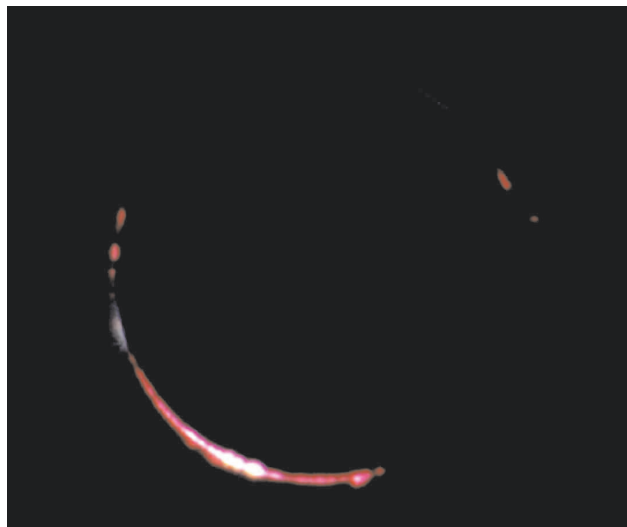


Figure 1.19 - The chromosphere clearly shows up as a pinkish-red fringe
in this picture taken during the eclipse on August 11th 1999
(external corona observed during the second contact; credit P., N. and J.F. Mein, DASOP, Observatory of Paris-Meudon).

From the chromosphere, the solar atmosphere that has become hotter is called the *solar corona*. This is the area that shines brightly enough to be visible during total eclipses. Between 2,500 and 3,000 kilometers, the temperature rises abruptly from 12,000 degrees to more than 1 million degrees 1,000 kilometers higher up, i.e. about 1,000 degrees per kilometer (see figure 1.16). It then goes on rising over about 15,000 kilometers to reach several million degrees. This area is called the transition region.

Beyond this starts what we could call the high solar atmosphere, bathing in its solar wind and "interplanetary" magnetic field. The wind can be characterized in a perfectly classical manner by the kinetic pressure it produces. Less familiar, perhaps, is the fact that the magnetic field, which produces a magnetic force, can also be characterized by a pressure²⁷. In the case of solar wind, these two pressures are quite comparable.

7. SOLAR DYNAMICS

We have known since the seventeenth century that solar activity is variable. However, even outside of its most agitated periods, the Sun displays dynamics of an extreme amplitude. In other words, although we tend to use the terms "calm" and "active" to describe solar activity, this is all relative: during a period of calm, the Sun can undergo eruptive bursts that affect it as a whole.

At the beginning of this book, the Sun and its atmosphere were described as perfect symmetrical and homogenous spheres. The study of solar activity shows this simplification to be incorrect. Our understanding of the Sun remains limited: the most recent observations have invalidated models without providing satisfactory alternative mechanisms. For the time being, the Sun can only be presented morphologically. In a manner, which is no doubt discretionary, we shall proceed to study four indicators of solar dynamics: solar spots, solar coronal holes, solar corona mass ejections and finally the large-scale structure of the streamers. These phenomena, which occur at increasing altitudes, constitute separate levels of solar activity which are, however, undoubtedly related.

7.1. SUNSPOTS. THE SOLAR CYCLE. PROMINENCES AND ERUPTIONS

Figure 1.20 shows the photosphere. Dark zones are clearly distinguishable: these are *sunspots*. They can easily be observed by taking a fairly wide piece of plastic piping (PVC as used for construction, for instance) and covering one end with a sheet of paper. Next, make a hole in the paper and direct that end of the pipe towards the

27 Appendix 10 contains elements concerning kinetic pressure and magnetic pressure.

Sun. On the other side, at a good distance from the pipe, place a sheet of white paper that will serve as a screen. The distance depends on the length of the tube and must be adjusted until the projection of the Sun is sufficiently clear²⁸.

Sunspots, sometimes seen in clusters, are mainly located at latitudes of between 40° North and 40° South. They appear to be darker because their temperature is lower: about 4,000 degrees. They therefore shine less brightly than the surrounding photosphere. Their diameter can exceed 300,000 kilometers. The magnetic field inside the spots is 100 to 5,000 times more intense than the surrounding field. A spot grows over a few days and a cluster of spots can last for 10 to 100 days. Since they are easy to observe, there has been a relatively precise count since 1610, that is, since the invention of the telescope. Regular counts have been carried out since the eighteenth century. The behavior of these spots is rather spectacular: there are

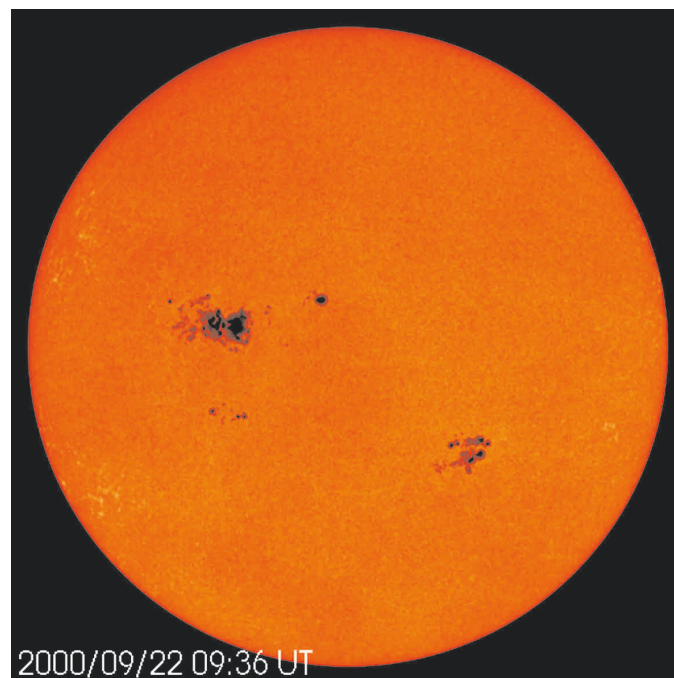


Figure 1.20 - This picture shows the highest number of sunspots groups observed during the present cycle (23rd) on September 20th 2000

The total area of photosphere covered by the spots amounts to more than twelve times the total area of the Earth (credit MDI/SOHO).

28 **Never observe the Sun with the naked eye, or with ordinary sunglasses!** This could lead to burning of the retina, and this damage could be permanent. This happened to 27 people in France during the eclipse on August 11th 1999. If you still have the special eclipse glasses lying in a drawer somewhere, do not use them again. They may have micro-scratches which would let the rays of the Sun through. Only use them if they have been kept in their original packing without being folded.

periods of maximum with more than 300 and periods of minimum with no spots at all! Since regular observation first began, the longest period without spots lasted for 70 years. This is the Maunder minimum, from 1645 to 1715. There have, however, been other, less pronounced periods with a low number of spots: between 1795 and 1830 (the Dalton minimum) and at the start of the twentieth century. When the number of spots is low the Sun is said to be *quiet* and when this number is high it is said to be in an *active period*. A great many other parameters characterize solar activity. For instance, the production of the ultraviolet flux, which we have already mentioned, varies in a manner very similar to that of sunspots.

For the last 250 years or so, the behavior of the number of spots appears to have been more consistent. Using as a starting point a quiet period, with no spots, if we wait for a few months we can see them forming at around latitude 45° North or South. Then, over the next five years, the area of formation moves nearer to the equator. As maximum activity is reached, 4 to 5 years into the cycle, new spots appear near latitude 5° but in decreasing numbers. After roughly eleven years, the Sun returns more or less to its original state. This cycle is called the *Schwabe cycle*.

The cycle becomes more complicated if the sign of the magnetic field of the sunspots is taken into account (North or South, positive or negative). The following behavior, sometimes known as the "Hale's Polarity Law" can then be observed: the polarity of the foremost spots in one of the hemispheres is the opposite of that in the

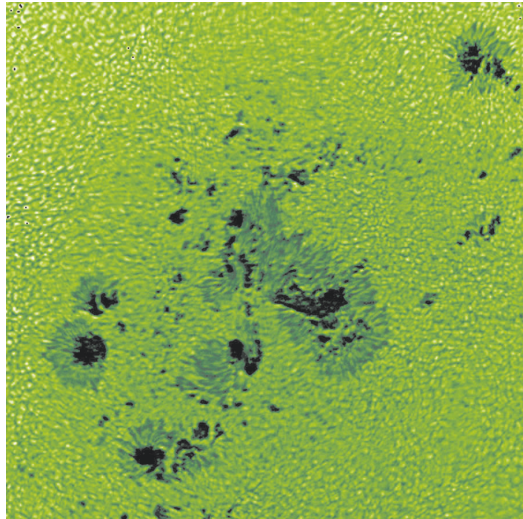


Figure 1.21 - A photograph of sunspots in the chromosphere, observed in the alpha ray of hydrogen (656.28 nanometers) on July 14th 2000, recorded at Dunn's Solar Telescope in the National Solar Observatory/Sacramento Peak Observatory
One side of this square represents 124,000 kilometers. This picture represents one of the major solar flares of cycle 23, known as the Bastille Day flare. Along with this flare there was an ejection of coronal matter at more than 1,500 kilometers per second (credit S. Koutchmy, CNRS-France; C. Viladrich).

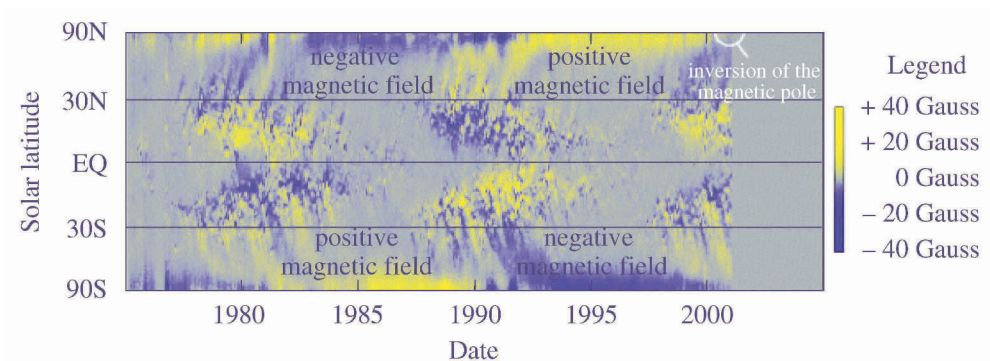


Figure 1.22 - This diagram shows the behavior of solar magnetic activity over two and a half solar cycles (since 1975)

The yellow areas show positive magnetic fields (North) and the blue areas negative magnetic fields (South). This is called a butterfly diagram since it shows a series of butterflies with one blue wing and one yellow wing. They represent the migration of the spots from the higher to the lower latitudes during the cycle. The butterfly reverses from one cycle to the next. The dipolar field can also be seen to reverse at the poles, as shown by the transition from one color to the other (credit Dr Hathaway, US National Solar Observatory – Kitt Peak; NASA).

other hemisphere. Furthermore, these polarities reverse from one cycle to the next. From a magnetic point of view, the solar cycle is twenty-two years rather than eleven. The 23rd Schwabe cycle began in May 1996 (cycles are dated from the first regular observations in March 1755).

The polarity of the spots is not the only magnetic indicator of solar activity. In fact, the behavior of the entire solar magnetic field is governed by this inversion: at times the magnetic north pole of the dipolar component points towards the geographical North of the Sun, and at other times towards the South. Maximum activity can be dated precisely from this reversal. The last reversal was in February 2001 for cycle 23, bringing the magnetic North pole to the geographical South of our star, where it will stay for a little more than ten years if the rhythm of solar cycles does not change. The Sun has a dipolar component of its magnetic field that is intense when activity is quiet then decreases until it disappears completely and reverses at the peak of solar activity.

At present, the models that simulate the generation of the solar magnetic field are unable to explain this reversal and the polarity of the spots. Why one phenomenon occurs when the activity of the cycle is at a maximum and the other during minimum activity, has not yet been understood.

The cycle of the spots is characterized by several indices. Historically, the index of Wolf is of major interest because it has been measured since 1848. It takes into account the number of clusters of spots and the number of spots, measured with nineteenth-century observation instruments. Continuous measurements are obtained

by applying correction factors to observations gathered with our modern, extremely precise instruments in order to allow comparison with those WOLF would have obtained with his own instrument. Amongst other norms of observation, index RI is used for monthly spots and index RI_{12} averaged over a year²⁹.

Since instruments are increasingly precise and we need an index that can be used as a geophysical record, we apply a correction factor k_{corr} that is adjusted according to the apparatus and takes into account its precision of observation so that two instruments of different precision give the same number. On figure 1.23 we show the evolution of R over a period of 63 years. The variation is relatively regular and determines the activity of the solar cycle.

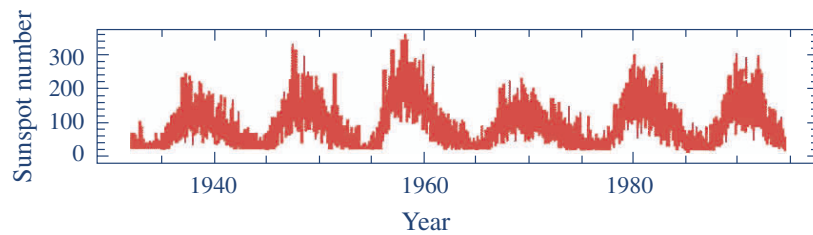


Figure 1.23 - The evolution of index R according to the years
The cycle of approximately 11 years is particularly visible.

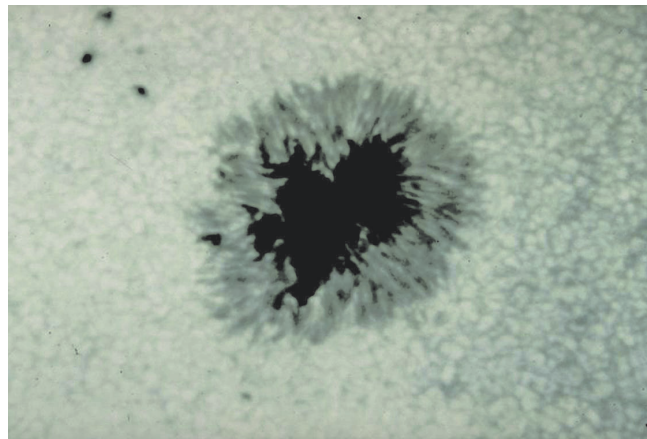


Figure 1.24 - A photograph of a sunspot and the surrounding granules
(credit S. Koutchmy, IAP-CNRS)

²⁹ The names of the indexes have been decided once and for all. Thus the index of Wolf is R and depends on the number of groups of spots G and the number of the spots T: $R = k_{corr}(10G + T)$. The mean index of spots per month is called RI_{12} . It is calculated using the relation

$$RI_{12} = \frac{1}{12} \left(\frac{RI(-6)}{2} + \sum_{m=-5}^5 RI(m) + \frac{RI(+6)}{2} \right) \text{ where } RI(m) \text{ represents the number of spots during month } m.$$

The eleven-year cycle may not be a true one. We may have been led astray by the very short period of observation. The cycles may vary, sometimes by 5 years and sometimes by 100 years, in a chaotic manner. This is one of the questions astrophysicists are trying to answer. This duration in itself – 11 years if we consider the number of spots and 22 years if we also take into account their magnetic polarity – poses a challenge. It calls to mind the time it takes for a surface element to migrate from the equator to the pole and then from the pole to the equator. Do these observations apply to correlated processes or are they independent? And where does the inversion of the dipolar field fit into the puzzle? There is no answer to these questions for the time being. As things stand, we are unable to assemble the pieces of these numerous but scattered and probably fragmentary observations to form a whole.

How are the spots formed? The surface magnetic field of the Sun shows up as field lines that are perpendicular to the surface but can be found both above and below the photosphere. This is what leads to the ejection of spicules. However, matter revolves more slowly at high latitudes than at lower ones and more quickly near the interior than near the surface. Under the effect of these rotations, magnetic field lines are distorted, coil up, twist... They become more complex in shape, as shown in figure 1.5 or photograph 1.25.

When the field lines become very dense, a sort of bulge is formed beyond the surface, giving rise locally to intense magnetic field tubes, perpendicular to the surface. In this zone, matter is slowed down (or organized) by the field lines, heat

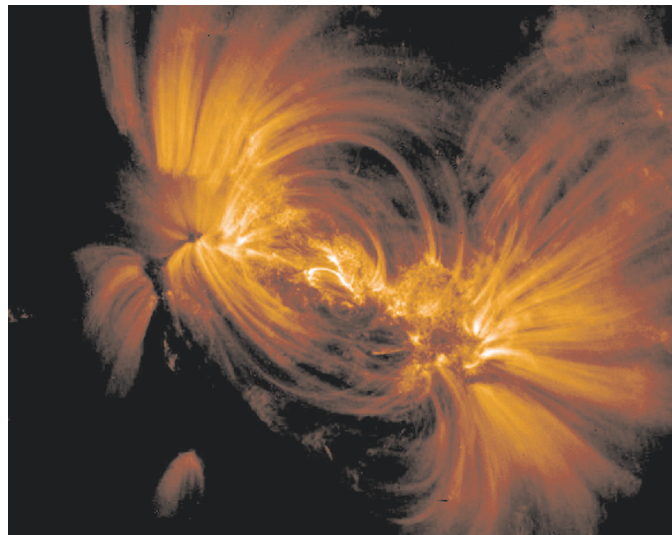


Figure 1.25 - The TRACE satellite reveals the magnetic loops above the photosphere

The scale of this picture is about 100,000 kilometers per 5 centimeters. It was taken at 17.1 nanometers, the characteristic wavelength of an emission at 1 million Kelvins (credit TRACE-NASA).

input from neighboring zones becomes difficult, the gas cools down, and a spot is born. Once it has formed, the spot is progressively eroded by the motion of the matter of supergranulations. The field lines produced by a spot favor the dissipation of energy towards the immediate atmosphere, giving rise to hot atmospheric zones which can extend into the solar corona: these are *chromospheric plages*.

A few days after they appear, a *filament* may form above the spots. This is a long structure that seems darker because it rises from the lower, colder layers towards hotter layers. They can be seen as dark areas on a light background (figure 1.27).

However, if this prominence appears on the side of the Sun (in relation to us) it will stand out as a light area on the dark background of the sky, like an arch that can reach up to 10,000 kilometers into the corona: it is then called an *active region prominence*. Its magnetic field can be as high as 50 Gauss i.e. 50 times the dipolar solar field. It is to be noted that the base of the prominences is not located on the sunspots, even though the two phenomena are probably connected. This is yet another question concerning solar astrophysics to which, as yet, we have no answer. Here are a few other questions: are the prominences loops, bubbles or arches? Sometimes they appear to be twisted: they are like rubber bands that have been twisted and turned until they snap or unwind very quickly. When we do this, energy is stocked slowly in the rubber band and then released violently. Does the same phenomenon occur in the prominences?

Sunspots have been known for several centuries. This is how C. FLAMMARION interpreted them more than a hundred years ago:

"The Sun will die. It is losing heat constantly because the energy it consumes as it radiates is, so to speak, unconceivable... If the Sun is still condensing sufficiently fast to offset such depletion (...) then it will not yet have started to cool down; otherwise, its cooling down period will already have begun. This is more likely the case since the spots that cover it periodically can only be regarded as a sign of this drop in temperature. The day will come when the spots will be far more numerous than they are at present and will start to cover a considerable area of the solar globe."

(C. FLAMMARION, *Popular Astronomy*, 1882)

A prominence can last for up to three solar rotations. Sometimes a bright point appears on a chromospheric plage and, in a matter of minutes, this point spreads until it covers an area of more than 50,000 kilometers in diameter. Then this brightness decreases in less than 3 hours. This phenomenon, known as a *solar flare*, is often preceded by a local prominence; the energy trapped in the prominence is suddenly released: up to 10^{23} joules are emitted in a few minutes. This is equivalent to the production of 30 million 1,000 megawatts power plants over a period of 100 years. This ejection comes with intense ultraviolet and X radiation as well as radio waves

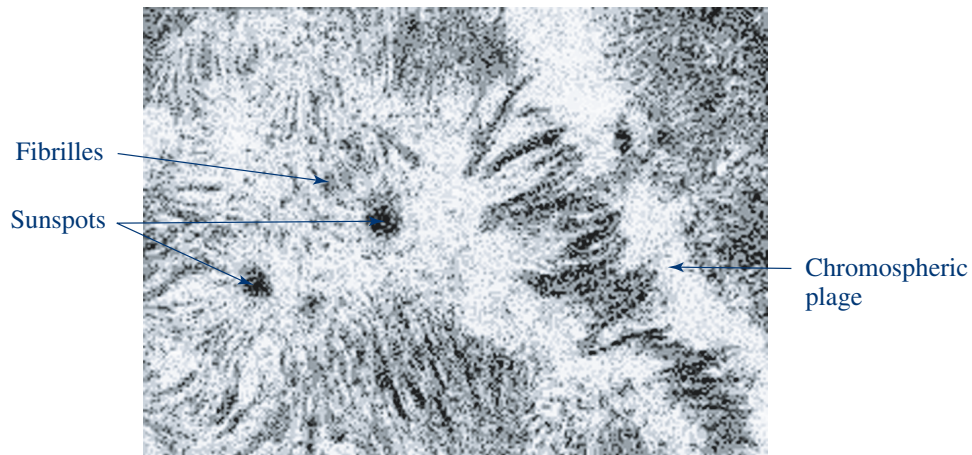


Figure 1.26 - This photograph, taken from the Pic du Midi on August 26th 1979 ($H\alpha$ ray) shows an active center on the chromospheric level with a network of fibrilles, two spots with reverse polarities and chromospheric plages
(credit Observatory of Midi-Pyrénées-solar team. Author: C.E. Alissandrakis)

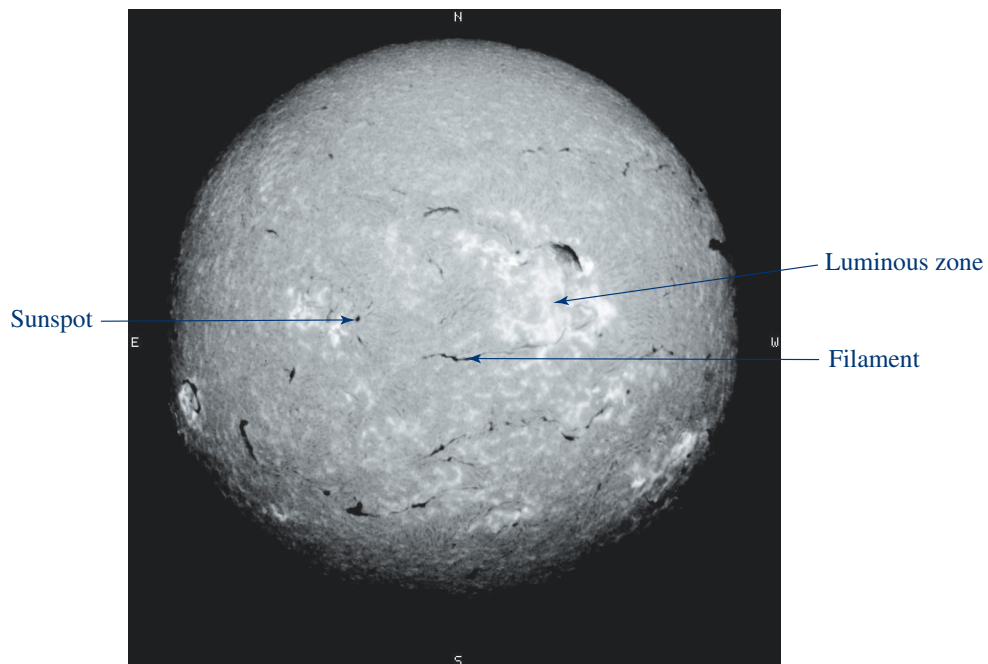
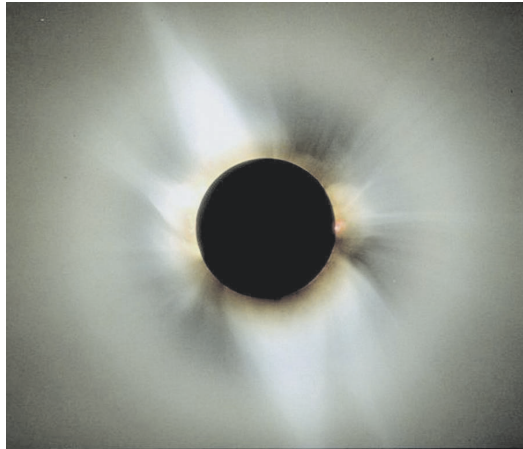


Figure 1.27 - A picture of the photosphere on November 5th 2000 (during an active period), taken by the Meudon spectroheliograph in $H\alpha$ (656.3 nanometers)
We can see a great number of filaments, sunspots, luminous zones.
(credit DASOP, Observatory of Paris-Meudon; CNRS)



***Figure 1.28 - Here we can see a prominence in the active region on the limb of the solar disk, photographed in white light during the total eclipse of the Sun on July 11th 1991, from Mauna Kea in Hawai
(credit S. Koutchmy, IAP-CNRS)***

and, frequently, the emission of high energy³⁰ –up to 1 gigaelectronvolt³¹– particles that can be sent out from the Sun. This is the second process –fundamentally sporadic in character– by which particle exchange takes place between the surface of the Sun and its atmosphere and then between the Sun and the atmosphere of the Earth. This phenomenon seems to occur more frequently when the filament is S-shaped or a reversed S. This observation is a sure-fire clue when it comes to forecasting solar eruptions. Figure 1.29 shows one of these eruptions.

Prominences of another type, unrelated to the presence of spots, are to be found above what is called the "quiet" Sun. They are known as "quiescent" prominences and can reach an altitude of 100,000 kilometers (0.15% of the Solar radius). They have a magnetic field of about 10 Gauss. The mass of the largest of these can represent up to one fifth of the coronal mass. They can also end in a flare, as shown on figure 1.30, and propel their matter out into space.

Flares are phenomena that involve tremendous amounts of energy. Temperatures of up to 25 million degrees can be reached in large flares. At temperatures such as these, iron is ionized 25 times.

30 Sometimes, one differentiates between eruptions that seem to eject primarily radiation ("flares") and those that transport energy in the form of matter ("eruption"). There is, however, no consensus on this terminology.

31 The electronvolt is the energy transmitted to an electron above the threshold of a difference in potential of 1 Volt. This energy is equal to 1.6×10^{-19} joules in the International System. Therefore 1 gigaelectronvolt is equal to 1.6×10^{-10} joules.

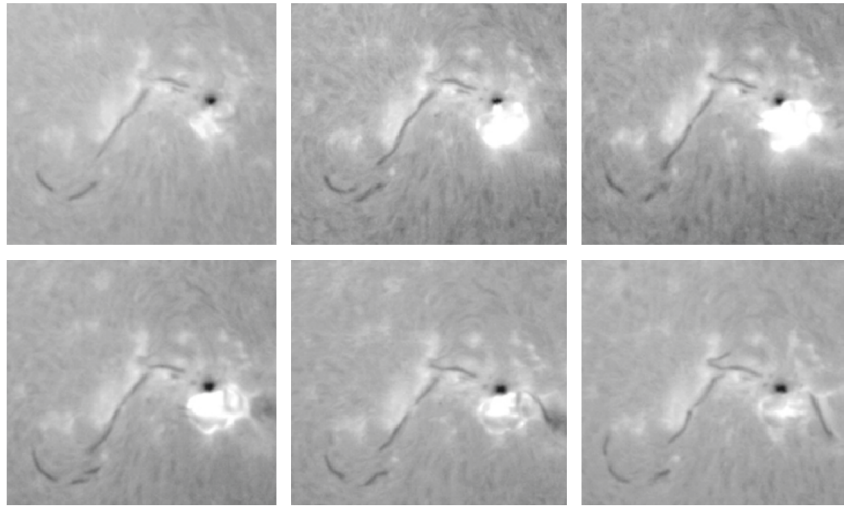


Figure 1.29 - In this figure, a solar flare spreads near and above a sunspot
Note the S-shaped filament that does not disappear as the flare develops. About 4 hours elapsed from the start of the phenomenon (top left) to the end (bottom right) (credit Hiraizo Solar Terrestrial Research Center, Japan).

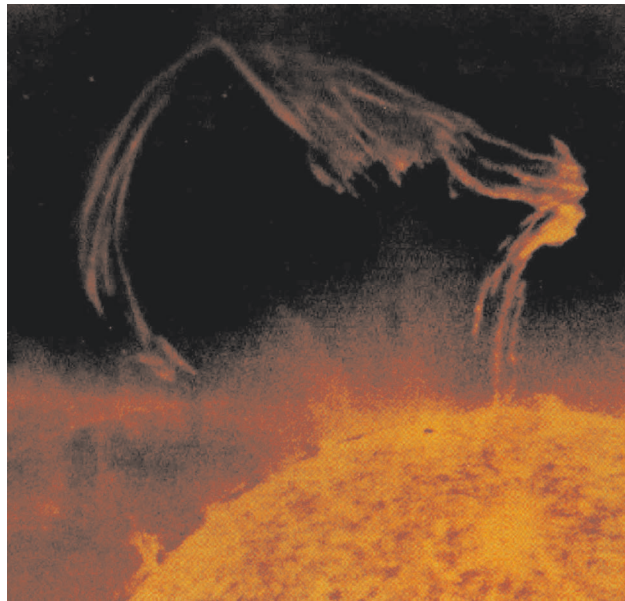


Figure 1.30 - A photograph of the chromosphere,
taken by the ultraviolet telescope on Skylab on August 9th 1973
(line of once-ionized helium HeII at 30.4 nanometers)
The diameter of the prominence that is bursting out into a flare is about 34 times that of the Earth (credit NASA).

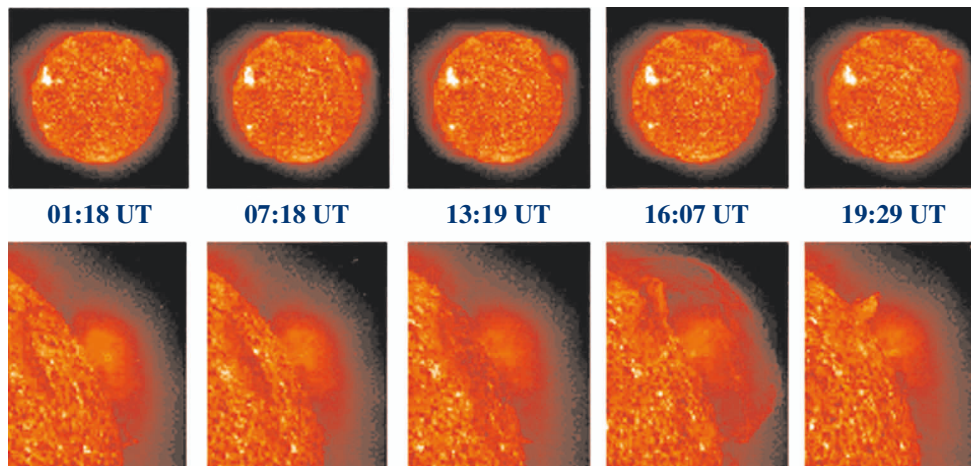


Figure 1.31 - Here is a spectacular series of pictures taken by SOHO on August 27th 1997, showing a magnificent solar flare

It was taken at 30.4 nanometers. This corresponds to a temperature of 60,000 to 80,000 degrees, far colder than the environment which is at 1 million degrees. On the fourth picture, at 16.07 UT, the diameter of the prominence is about 28 times that of the Earth (credit SOHO/EIT consortium).

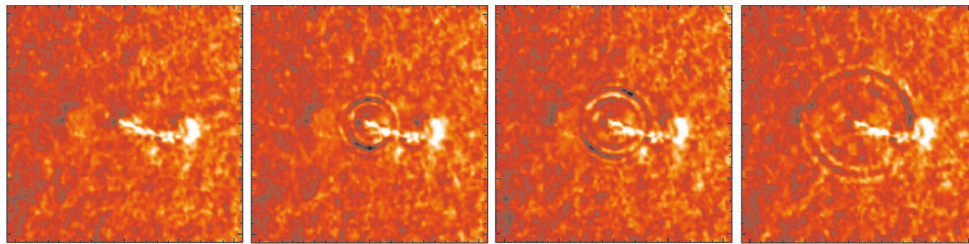


Figure 1.32 - A seismic wave on the surface of the Sun, on July 9th 1996, combined with a solar flare and, probably, a coronal mass ejection

Within an hour, the wave is ten terrestrial radii from the flare (credit SOHO/MDI).

Flares can sometimes lead to seismic waves that spread over a very large part of the Sun. Figures 1.31 and 1.32 illustrate these phenomena of our star during a period, which can still be considered as "quiet"!

7.2. CORONAL HOLES. FAST WIND

We have explored the solar atmosphere starting from the surface of the Sun, the photosphere. Recall (figure 1.16) that at an altitude of about 3,000 kilometers and over a few tens of kilometers, the temperature increases suddenly from 10,000 to 100,000 degrees and very quickly reaches several million degrees. This area of intense heat is called the transition region. What sort of structures can be found above this? Observation of the Sun with X-rays, almost systematically shows large,

not very bright plages. These are extremely mobile low-density structures that are cooler than the corona (1 to 2 million degrees) and can cover up to one third of the Sun. They are called *coronal holes*. The principal holes are often located at the poles and their magnetic field opens widely toward space, providing a sort of exit for the solar wind. They cover a larger area during periods when the Sun is quiet and shrink when it is active. The physics of coronal holes remains, by and large, unknown.

Large tongues of matter called *plumes* break loose from coronal holes. These plumes are far bigger than the spicules: a few tens of thousands of kilometers compared with a few thousand. Their temperature is about 1 million degrees, that is, ten times greater than that of the spicules. Their origin is still uncertain. Wind blows almost twice as fast as the solar wind that blows from the spicules. Called *fast wind*, it was measured by the ULYSSES probe beyond a latitude of 20 degrees. It normally blows at even higher latitudes but the Coriolis³² effect tends to deflect it back toward the solar equator i.e. toward the ecliptic plane³³.

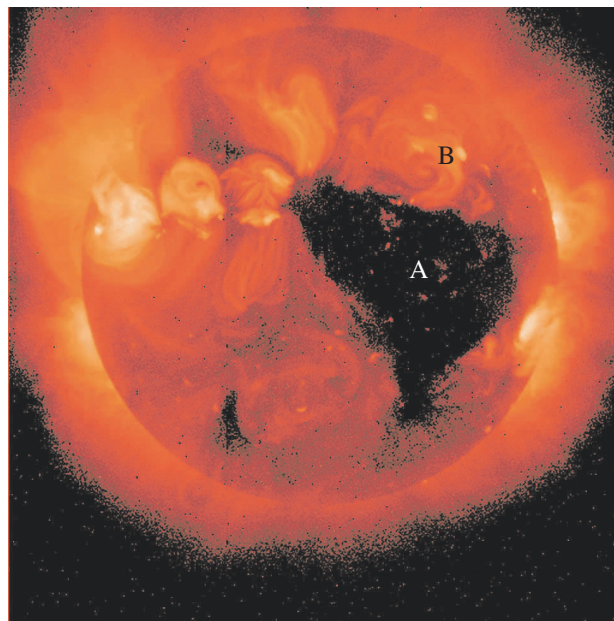


Figure 1.33 - The Sun photographed in X-rays by the YOHKOH satellite on December 5th 1999

The coronal hole (A) and the solar dynamics are clearly revealed. One of the reasons it is so difficult to compare pictures is that we must bear in mind that different layers of the Sun are observed with different wavelengths. We can also see coronal loops (in B, for instance) plotting the local magnetic field (credit Japanese Institute of Space and Astronautical Science (ISAS/LPARL); NASA).

³² See the revision on the force of Coriolis in appendix 11.

³³ The plane of the Earth's orbit round the Sun.

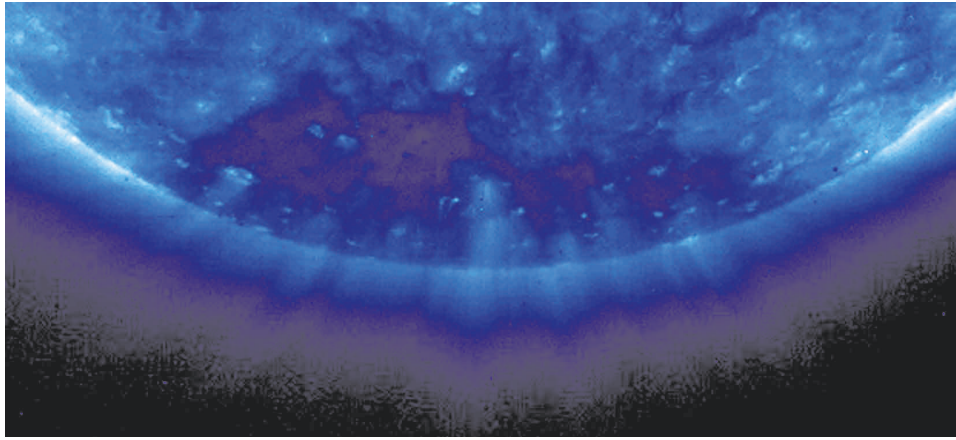


Figure 1.34 - This picture was taken at 17.1 nanometers, with the radiation emitted by eight or nine times ionized iron
 At this wavelength we can observe (in processed colors) a darker area at the pole which is a "coronal hole". Plumes are huge strands of matter above this coronal hole (credit EIT on SOHO).

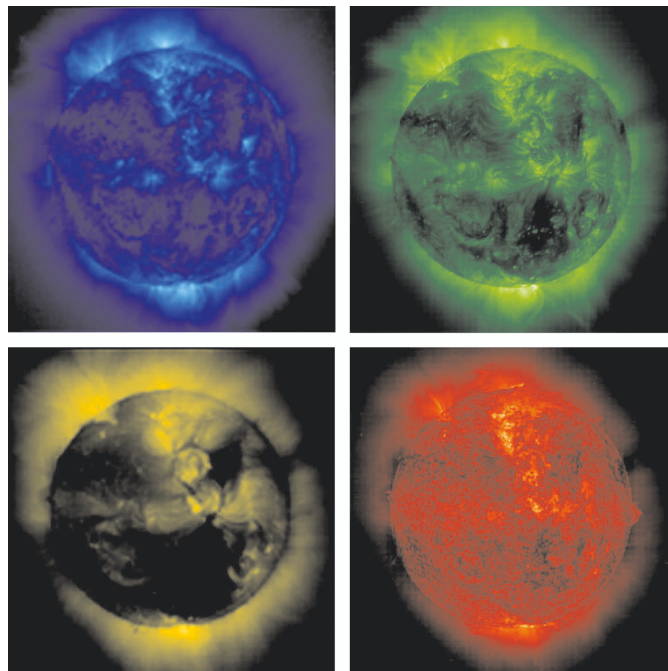


Figure 1.35 - On December 6th 1991, EIT took four photographs of the Sun, at 17.1 nanometers (top left), 19.5 nanometers (top right), 28.4 nanometers (bottom left) and 30.4 nanometers (bottom right)
 Coronal loops can be observed on all these pictures, meaning that they occur at various altitudes above the chromosphere. The coronal holes are clearly visible on the picture of the fourteen times ionized iron at 28.4 nanometers.

When coronal holes occur at lower latitudes, wind blowing at 700 kilometers per second mingles with wind at 400 kilometers per second. It pushes it about to a certain extent, considering the low number of collisions that can occur, rubs up against it and then slows down, accelerating the other wind. Perturbations are created, shattering the pattern of the solar wind. The magnetic field also starts to vary, in function of the speed and the direction of the particles. At Earth level, anything can happen: reversals of the solar magnetic field: "North" swings around to "South" then back to "North" in a matter of a few tens of minutes... Bursts of hot, rapid particles are quickly followed by slower blasts... There will naturally be many repercussions if they hit the Earth.

7.3. THE LARGE-SCALE STRUCTURE: CORONAL STREAMERS

Let us now look into large-scale solar activity, concerning phenomena of more than two solar radii above the photosphere. During an eclipse, or when using a coronagraph³⁴,

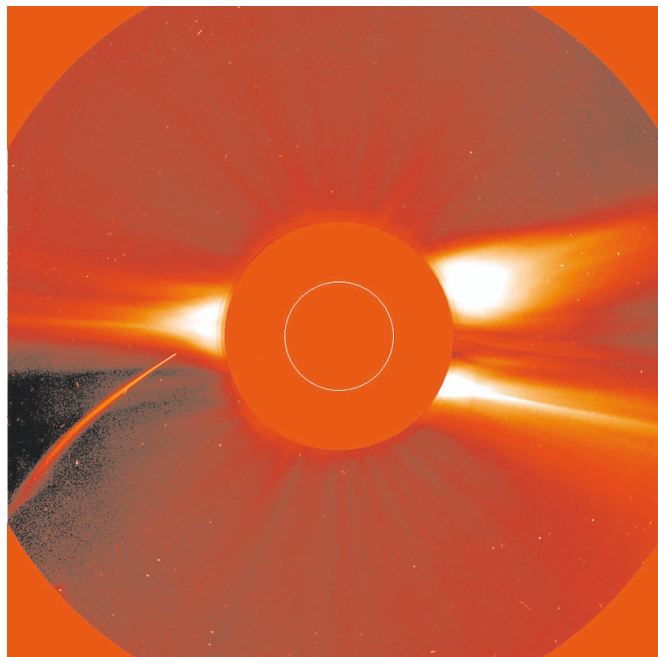


Figure 1.36-a - In this photograph, the Sun is occulted by a coronagraph
To prevent the instrument from being dazzled, the occulting disk is far larger than the apparent size of the Sun, represented by a yellow circle. In the corona we can observe three particularly bright coronal streamers. On the left we can also see the trail of a comet moving towards the Sun (credit LASCO/SOHO).

³⁴ A coronagraph simulates an eclipse: an occulting disk is placed in the center of the telescope so as to block out the intense direct light of the photosphere and observe the diffuse and not very bright light from the corona.

structures in the form of streamers appear in white light. An analysis of their magnetic field shows that the field lines are closed at their base and open up above about one solar radius. At the interface between closed and open parts, a neutral layer appears to separate areas with oppositely directed magnetic fields. This model is depicted on one of the streamers in figure 1.36-a, enlarged on figure 1.36-b.

During a period of low solar activity, it is quite common for only two streamers to be visible on either side of the Sun. They then appear to follow a line that has one polarity to the North and the opposite polarity to the South, i.e. we have a coronal magnetic field reversal line. This does not necessarily follow the solar equator meaning that during the 27 days of solar rotation the Earth is subjected to a magnetic field which is at times directed toward the South and at others toward the North. However, when the Sun is in an active phase, the magnetic structure of the corona

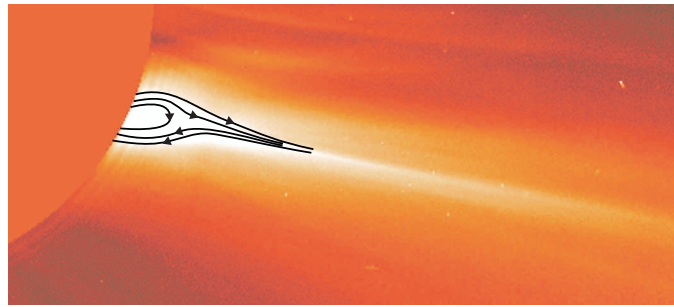


Figure 1.36-b - An illustration of the model of streamers

The lines represent the magnetic field lines and the arrows the direction of the field.

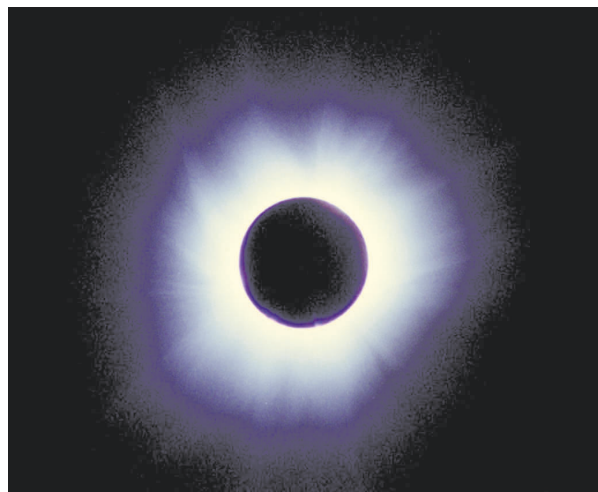


Figure 1.37 - The solar corona photographed during the total eclipse of the Sun on August 11th 1999
(credit P., N. and J.F. Mein, DASOP, Observatory of Paris-Meudon)

becomes more complex. Figure 1.28 shows an example with several, as yet quite distinct streamers. At the height of its activity, the magnetic structure is disturbed to such an extent that streamers develop in all directions. The corona then appears to be spherical, as shown in figure 1.37 and the Earth undergoes a more complicated regime of interplanetary magnetic field reversal.

7.4. CORONAL MASS EJECTIONS

These are undoubtedly the most important solar phenomena as far as space weather is concerned. Their existence was discovered only recently, when in 1973 it became possible to send coronagraphs up into space. Coronal mass ejections are observable changes in the coronal structure, lasting from a few minutes to a few hours. They are bright in visible light in the corona and, above all, entail an expulsion of plasma and magnetic field from the corona toward interplanetary space. Their scale far exceeds that of flares: a coronal mass ejection can affect more than a third of the corona, at altitudes of several solar radii. Until 1979, it was thought that flares gave rise to ejections. This is not so: the two phenomena can be observed separately or simultaneously but one does not systematically precede the other. Their structure also defies analysis and their explosion has not been explained. To get an idea of the

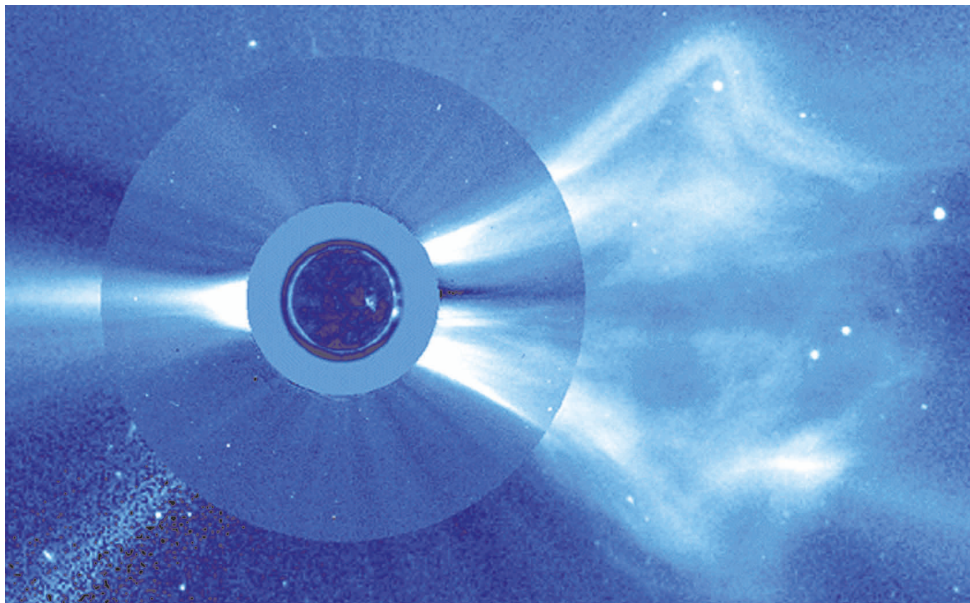


Figure 1.38 - On the right of the picture, a coronal mass ejection

This model, made using data from several instruments carried onboard SOHO, also shows the Sun in the center in dark blue. The white dots are stars. The magnetic structure of the corona can be seen clearly above the coronal holes (credit LASCO/SOHO).

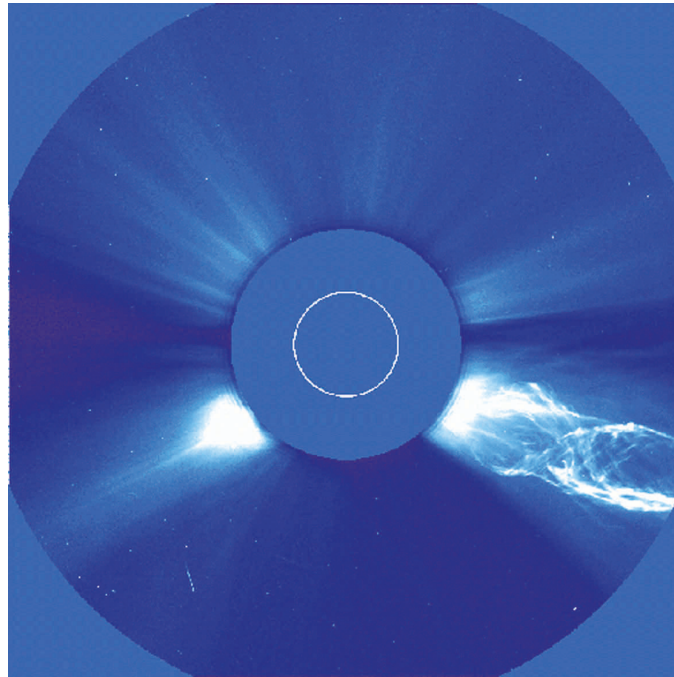


Figure 1.39 - On the right, a coronal mass ejection (combined on that particular day with a solar flare)

Its size can be compared to that of the streamer on the left. The coronal holes are the darker parts of the solar atmosphere. The white circle indicates the size of the Sun (credit LASCO/SOHO).

scale of these phenomena, imagine a tornado 5,000 kilometers in diameter capable of devastating Europe in a few minutes and producing winds powerful enough to destroy all dwellings over the whole of our planet and all this happening several times a day. Their occurrence, on the Sun, varies from a half to three times per terrestrial day, depending on whether solar activity is in a low or high period. Coronal mass ejections occur at all periods of the cycle. Observations appear to have shown that they happen nearer to the equator when solar activity is at its lowest and then over ever-increasing latitudes until they reach $\pm 60^\circ$.

Although their number varies with the solar activity, their distribution is different from that of sunspots, so it is not possible to establish a correlation between the two phenomena any more than it is possible to link flares and coronal mass ejections.

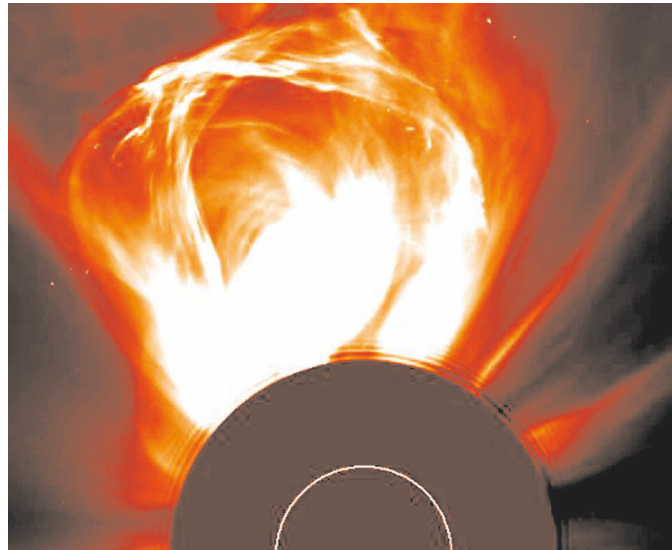
Whereas solar wind causes the Sun to lose 10^{14} kilograms of its mass per day, ejections are responsible for a loss of "only" 10^{12} kilograms. The distribution of the speed of the ejected particles is quite variable, ranging from 100 to $2,000 \text{ km s}^{-1}$, with a mean value of about 300 km s^{-1} .

When an eruption occurs, lost matter leads to local depletion and a temporary coronal hole, the immediate filling of which gives rise to displacements of matter in the form of waves³⁵ that spread over the whole corona.

The origin of coronal mass ejections is a mystery. They take with them the local solar magnetic field with components in all directions. The two cycles of observations available have shown that the field is directed towards the South at the start and towards the North at the end. However, we cannot draw conclusions after just two cycles. Once in space the front of the ejection is called a magnetic cloud and it is important to predict which of these will affect the Earth.

Although it is now possible to observe the emanation of ejections that occur on the sides of the Sun, those that come towards us are not very bright and remain invisible since they are hidden by the intense brightness of the solar disk. They can only be conjectured by their effects: the reconstitution of the corona and, for larger-scale ejections, a halo that surrounds the whole Sun. However, these halo ejections do not all collide with our planet. Some are even hurled in the diametrically opposite direction, originating on the hidden side of the Sun.

Like solar flares, but with very different speed distribution and on a far larger scale, coronal mass ejections obviously perturb the solar wind.



***Figure 1.40 - A spectacular coronal mass ejection
as observed by the LASCO coronagraph on SOHO
The size of the Sun is indicated by a white circle.***

35 Called "Moreton waves" after the person who first observed them in 1961. Their connection with the seismic waves shown on figure 1.31 has not yet been proven, although several scientists think there is one.

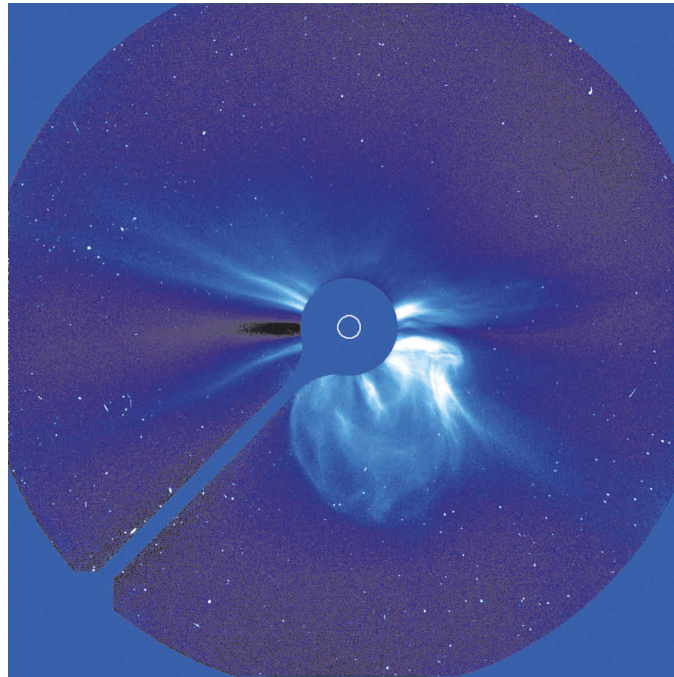


Figure 1.41 - A coronal mass ejection on March 29th 1998
*The line on the left is the bracket of the coronagraph.
The size of the Sun is shown by the white circle.*

7.5. AN INDEX OF SOLAR ACTIVITY

As we have seen, solar activity takes the form of many phenomena which are often difficult to quantify or even, in the case of extreme ultraviolet, to measure. Yet it is of the utmost importance to calculate the rate of activity of our star. The number of sunspots is not sufficient: for instance it shows neither the flares nor the coronal mass ejections. We need to find another indicator of activity or, in modern terms, a *proxy*. But it is not easy to decide on what we should focus: the number of spots, the number of filaments and prominences, the number of coronal mass ejections at a given time...?

With regards to the object of this book, the requirement is an indicator of solar activity in the widest sense. What comes to mind is solar radiation on the radio scale (with wavelengths of about a centimeter). This depends on the temperature of the location from which it is emitted and its electronic concentration, both of which vary according to the activity. Furthermore, it has the tremendous advantage of being measurable from Earth.

The choice of the wavelength adopted at the international level—10.7 cm—was widely determined by the development of techniques during World War II. Its intensity is called the *flux at 10.7 centimeters* or *decimal index*, written $f_{10.7}$ and expressed in

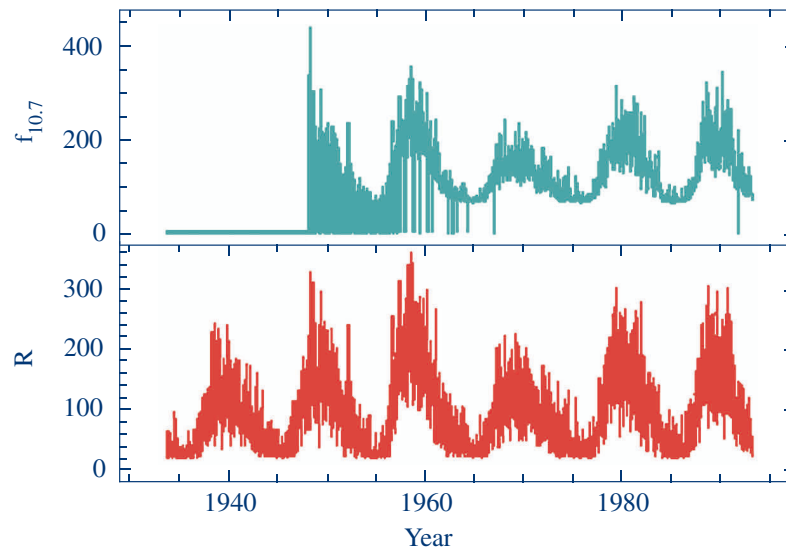


Figure 1.42 - This figure represents the progression of the number of sunspots (see figure 1.23). Above, the variation of decimal index $f_{10.7}$ which, as we can see, is a good indicator of solar activity

$10^{22} \text{ W m}^{-2} \text{ Hz}^{-1}$. This unit is called the solar flux unit and sometimes the Jansky³⁶. It varies from a few tens to approximately 350. The intensity of the flux at 10.7 cm has been measured regularly since 1947 but it was a lot later, in 1964, that it was shown to be an excellent indicator of global solar activity. However, other wavelengths could have served the purpose just as well.

For lack of anything better, all present-day geophysical models use $f_{10.7}$ as an indicator of solar activity. However, considerable research is being carried out to find a better-defined, more precise indicator, so as to take prominence radiation into account one way or another.

8. THE SUN: AT THE SOURCE OF SPACE WEATHER

The Sun, our star, has been introduced in this chapter. It floods the Earth with radiation and matter that trigger various kinds of perturbations. Let us summarize some major points of this chapter.

The solar mass of 2×10^{30} kilograms and its diameter of 1.4×10^9 meters mean that the Sun is a star of only average size. The temperature of its core, where nuclear fusion takes place, is 15 million Kelvin. On the surface, in the photosphere,

³⁶ Note that this unit is that of spectrum lighting in the International System, divided by 10^{22} (see photometric values in appendix 6).

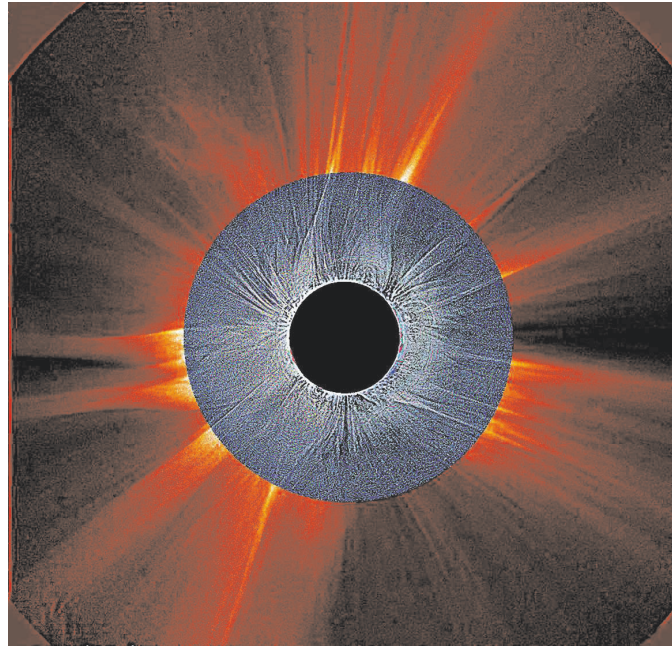


Figure 1.43 - A model of the different atmospheric layers of the Sun, showing the magnetic structure at various scales during the total eclipse on August 11th 1999
(credit S. Koutchmy, IAP-CNRS, LASCO/SOHO)

the temperature drops to 5,800 Kelvin. The Sun consists mainly of hydrogen (about 94%) and helium (6%). The energy produced is the result of the fusion of hydrogen into helium.

Solar activity occurs over periods of roughly 11 years, characterized by a great many phenomena: reversal of the dipolar magnetic field, the sunspot cycle, variations in the number of flares and coronal mass ejections, and in the electromagnetic flux...

Two major sources of energy (sources for the Earth, that is, but depletion for the Sun) have their origins on the Sun and rule over the formation of the ionized environment on Earth: particles and radiation.

Particles constitute the solar wind that can be divided into slow and fast winds. These winds are permanent and, at Earth level, vary in speed from 200 to 800 km s⁻¹. Their concentration is roughly ten particles (*five ions and five electrons*) per cubic meter.

The second permanent source is electromagnetic radiation, in which extreme ultra-violet plays a specific part.

There is a third specific source of energy that originates in the eruptions or coronal mass ejections. This source is sporadic and varies according to solar magnetic activity. The speed of particles is often higher than that of the permanent solar wind, sometimes enabling them to reach the orbit of the Earth in as little as ten hours. These eruptions are often accompanied by a significant increase in electromagnetic radiation.

Table 1.5 - A comparison between sources of solar energy

	Nature	Solar cover	Effects felt on the Earth after a period of
Slow solar wind	Permanent	The whole of the Sun, coronal holes excepted	3 days
Fast solar wind	Permanent	Coronal holes	2 to 3 days (mingled with slow solar wind)
UV spectrum	Permanent	The whole of the Sun	8 minutes
Flares and coronal mass ejections	Sporadic	From slight to one third of the Sun	a few hours to three days

The total energy emitted by the Sun is approximately 10^{27} Watts. 1,000 billion Watts per square meter are emitted at the level of the photosphere in the form of photons, in a stable manner; over the entire star. The ultraviolet is only a small part of the electromagnetic radiation since, on average, it corresponds to an emission of $100,000 \text{ W m}^{-2}$ at the level of the Sun. This is a highly variable source. Solar wind in itself, fast and slow together, "only" carry away $10,000 \text{ W m}^{-2}$. It is emitted over the major part of the sphere.

The flux of energy per unit of surface, carried by the particles when eruptions occur, can be as much as a million Watts per square meter and radiation emittance can increase up to 100 billion Watts per square meter.

When it comes to electromagnetic energy, the Earth receives 1,366.1 Watts per square meter (when the Sun is at the zenith). This is a mean value, the impact of which on our daily life is known. However, who can know what repercussions variations in solar emission whether in the form of radiation or particles might have? An explanation can be found in the next chapter that contains a description of the Earth and its magnetic and atmospheric environment.

Chapter 2

THE EARTH

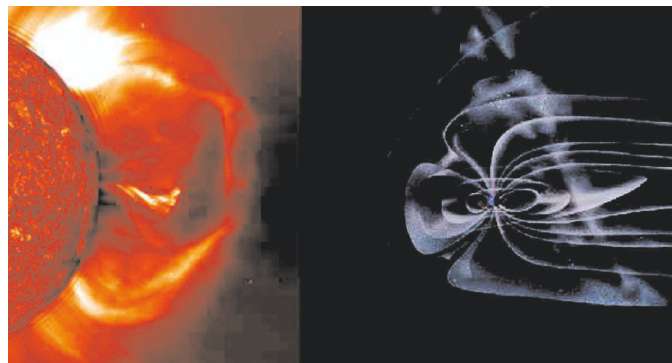


Figure 2.1 - On the left, this photographic construction shows an eruptive solar occurrence and on the right an artist's impression of the Earth in its magnetic field represented by the pale lines (credit SOHO for the Sun, NASA-NOAA for the Earth, taken from the logo of NASA's WIND satellite)

What effect will the solar wind and these electromagnetic waves have on the behavior of the Earth? Which phenomena also occur in a terrestrial environment? To answer these questions we need to know more about some of the characteristics of our planet.

1. THE EARTH WITHIN THE SOLAR SYSTEM

The Sun is surrounded by a system of bodies of different sizes and orbits. The first four planets¹, Mercury, Venus, the Earth and Mars are said to be terrestrial, due to their size and composition, which closely resemble those of the Earth. Jupiter, Saturn, Uranus and Neptune are giant, gaseous planets and are, therefore, very different from the telluric planets. These eight planets revolve around the Sun in

¹ The planets are usually classified according to their average distance from the Sun, starting with Mercury that is closest and ending with far-off Pluto.

roughly the same plane, the ecliptic plane. Finally, we have the pair formed by Pluto and Charon; this is a curiosity in the solar system, with an orbit that is extremely inclined on the ecliptic (7.2 degrees) and, for Pluto, a diameter of 2,280 kilometers, that is, two-thirds of the diameter of the moon. Those two bodies were in fact captured by the Sun rather than formed like the other planets.

Table 2.1 - A few parameters concerning the planets of the solar system

	Revolution round the Sun ("tropic period")	Semi-Major axis [millions of km /AU ²]	Diameter at the equator [km]	Mass (Earth = 1)	Volume (Earth = 1)	Rotation on its axis (day)	Gravity (Earth = 1)
Mercury	88 days	57.9 / 0.387	4,879	0.055	0.06	58.65	0.38
Venus	224.7 days	108.1 / 0.723	12,104	0.815	0.86	243*	0.9
Earth	365.26 days	149.6 / 1	12,756	1	1	1	1
Mars	1 year 321 days	227.9 / 1.524	6,794	0.107	0.15	1.026	0.38
Jupiter	11 years 314 days	778.3 / 5.203	142,984	317.8	1,315	0.41	2.53
Saturn	29 years 167 days	1,429 / 9.555	120,536	95.16	757	0.427	1.07
Uranus	84 years 7 days	2,875 / 19.21	51,118	14.54	62.9	0.45*	0.92
Neptune	164 years 281 days	4,504 / 30.11	49,528	17.15	57.5	0.67	1.14
Pluto	247 years 362 days	5,915 / 39.54	2,390	0.0022	0.007	6.39	0.06

* *Venus and Uranus revolve in a retrograde manner i.e. in the opposite direction to the Earth.*

-
- 2 The unit usually adopted for distances within the Solar System is the Astronomical Unit (AU). This corresponds to the mean length of the Semi-Major axis of the orbit of Earth i.e. 149,597,870 kilometers. Between the beginning and the end of the year, the distance between the Earth and the Sun varies from 147 to 152 million kilometers. The first value, that corresponds to the point of the orbit of a planet or a comet that is nearest to the Sun, is called the perihelion and the second, which is the furthest away, is the aphelion. The first approach to the movement of the planets around the Sun is described by Kepler's Laws, found in appendix 12.

The diversity of the situations of the planets is quite remarkable. The presence of both an atmosphere and an intrinsic magnetic field on Earth are not without consequences on its relationship with the Sun. This case is unique amongst the telluric planets that have either one or the other of these characteristics. The giant planets are also magnetized but, unlike Earth, their atmosphere has no discontinuity with the planet itself: from the core toward space the gas they are made up of changes gradually from a compact state called "metallic" to a gaseous state which, as far as we know, is closer to the pressures found on Earth.

The solar system contains other bodies: asteroids and comets of various sizes, shapes and orbits. Asteroids are fragments of rock that circulate in thousands, especially in a ring between Mars and Jupiter. Comets are bodies of ice and dust.

The Earth is the third planet from the Sun and its rotation axis is at $23^{\circ}27'$ on the ecliptic plane. This inclination explains the seasons and defines the latitudes of the two tropics where the Sun is immediately above at noon during the June solstice (Cancer) and the December solstice (Capricorn).

We have just mentioned latitude. Now we should perhaps mention position and time.



Figure 2.2 - An artist's impression of the solar system

The scales of distance do not correspond to the scales of volume (see table 2.1). From the Sun, on this drawing we can see Mercury, Venus, the Earth then Mars. Beyond these there is an asteroid belt and a comet. Its path is represented by an unbroken line but its tail is opposite the Sun. Next, come the giant planets, Jupiter, Saturn, Uranus and Neptune. Finally, top left, we have Pluto (credit Editions du Sorbier, all rights reserved).

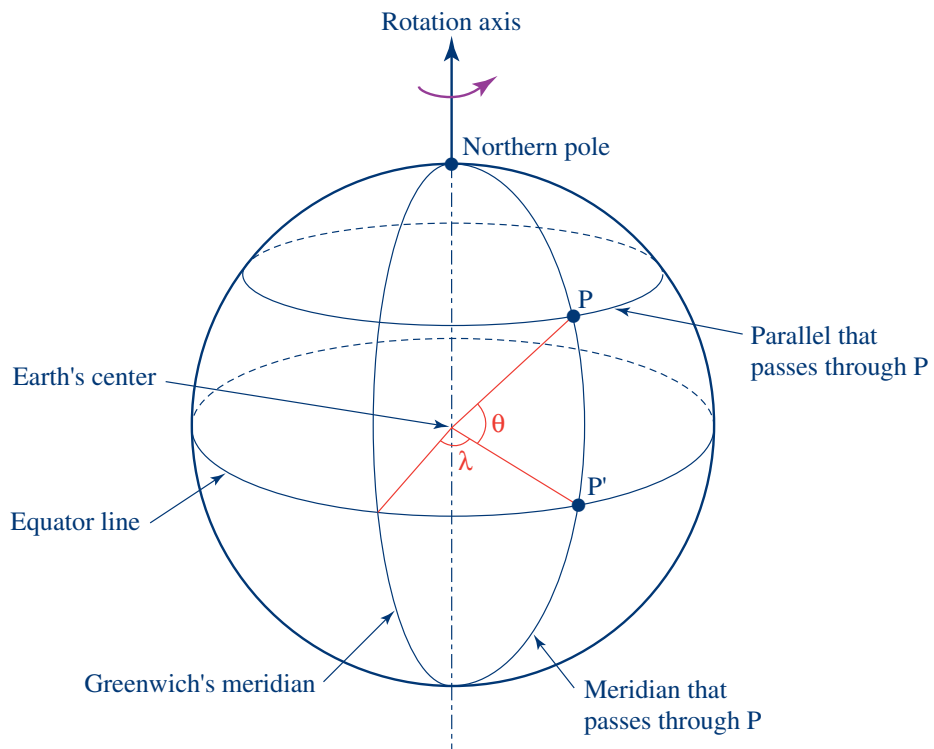


Figure 2.3 - The geographical coordinates

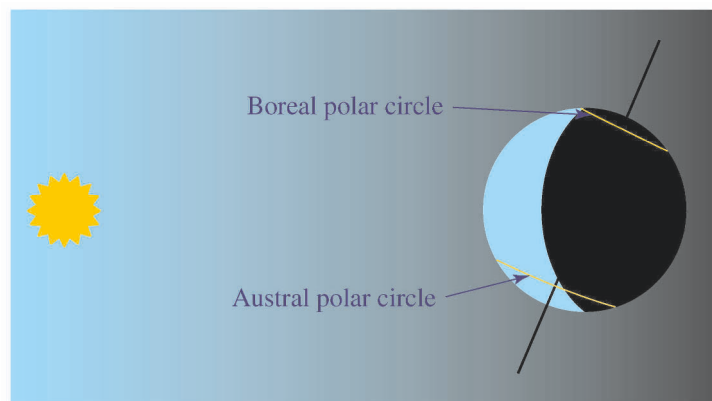


Figure 2.4 - The polar circles during the boreal winter

Terrestrial geographical coordinates use a system of imaginary lines (figure 2.3). The lines that join the two geographical poles are the meridians and the lines that are perpendicular to the meridians are the parallels. By agreement, the meridian that passes through the town of Greenwich in Great Britain is meridian zero. The longitude of a point P (positive toward the east, negative toward the west) is angle λ measured on the same parallel between a straight line connecting the center of the Earth to the Greenwich meridian and a straight line connecting the center of the Earth to the meridian that passes through a point P. It is generally expressed in degrees. For instance, the longitude of Paris is $2^{\circ}20'14''$.

The parallel that passes at the same distance between the two geographical poles is the geographical equator. Take a point P whose meridian cuts the equator at P'. The latitude of point P is the angle θ formed by the line that runs through the center of the Earth and P' and the line that runs through the center of the Earth and P. It is positive toward the North and negative toward the South and is generally expressed in degrees.

The ways in which time is measured are relatively complicated (see appendix 13) but space weather can be approached via three units of time. The first is simply the time of the place where we are in relation to the Sun. This is known as local time (abbreviated as LT): when the Sun is at the zenith, it is twelve noon in local time. However, back in the nineteenth century, international exchanges led to the introduction of a time common to all countries, the universal time (UT) which uses the Greenwich meridian as a reference. Universal time i.e. Greenwich Mean Time is the same everywhere on Earth. The last time is the legal time chosen by each country or group of countries; the area extending from the west of Spain to the east of Poland, which is about 3,000 kilometers wide, does not have an identical local time throughout the countries: the Sun rises over Corunna nearly three hours before rising over Warsaw. However, the countries within this area chose to have the same time, one hour ahead of Greenwich Mean Time in winter and two hours ahead in summer.

Due to the inclination of the Earth there are two regions, one in the North and one in the South, where on at least one day in the year the Sun does not rise or on at least one day in the year it does not set. The limits of these regions, at a latitude of $66^{\circ}33'$, are the polar circles (Arctic or Boreal in the North, Antarctic or Austral in the South).

2. THE INTERNAL STRUCTURE OF THE EARTH: THE GEOMAGNETIC FIELD

A first approach is to liken the Earth to a pile of spheres, each with its own characteristics. In the deepest part, it has an internal nucleus (or core) consisting of nickel and iron. Between – 6,370 kilometers and – 5,150 kilometers (that is to say, from the center of the Earth to a distance of 1,220 kilometers from the center) the

nucleus is probably solid. Its temperature is about 5,000 Kelvin; this means that intrinsic magnetization of the center is impossible since it is above the Curie³ temperature of iron, that is 1,043 Kelvin.

Beyond this, through to – 2,900 kilometers, the iron becomes liquid: this is the external nucleus. Iron and nickel still account for the greater part but are probably associated with other, lighter elements such as oxygen, sulfur, silicon or carbon. The temperature drops from about 4,800 Kelvin at the inner edge of the liquid nucleus to 3,100 Kelvin at its outer edge. Here we are in a rather unusual medium i.e. a liquid, conducting metal, the properties of which are, in many ways, comparable to those of a plasma. Amongst other properties, let us mention the great mobility of the electrons. Little by little, part of the iron in the liquid nucleus crystallizes and is deposited on the solid core. Due to the progressive loss of its iron, the liquid nucleus is proportionally enriched in light elements, sulfur and oxygen, particularly the lower layers, closest to the solid core. This crystallization is exothermic: it gives off heat that feeds the liquid nucleus. This energy is consumed partly by convection movements: the liquid metal near the core becomes less dense and warms up. It rises towards the outer edge of the liquid nucleus, towards the shell of the Earth. As it rises, it is subjected to a decline in gravity and increasing centrifugal forces due to the rotation of the Earth on its axis. All this results in a general movement of the liquid nucleus, like that of a slow river spiraling around itself. The rotating motion of the charges is at the origin of the dipolar terrestrial magnetic field.

Other movements can destroy the dipolar structure of the field, by creating local anomalies that can be measured at the surface of our planet. We are now convinced that the liquid core is active and turbulent. Furthermore, the magnetization of the superficial layers of the planet is a second source of magnetic anomalies that can be measured at the surface and which, unlike the former, does not change with time. The third source of anomaly is dealt with very fully further on since it is directly connected to the solar wind.

When the spiral of the "plasma river" in the terrestrial nucleus is too tightly wound, it unwinds by turning round. The magnetic field of the Earth then reverses. Over the last 4.5 million years, the field has reversed 25 times at intervals that do not appear to be regular.

3 In a magnetic field $\vec{B}$ a magnetic material acquires a magnetization $\vec{M}$ (in $A\ m^{-1}$) proportional to $\vec{B}$ if it is paramagnetic. The factor of proportionality is approximately the ratio between the magnetic susceptibility χ_m that characterizes the material and the relative permeability μ_p that characterizes the media in which the field is propagated. Ferro-magnetic media such as iron, cobalt, nickel are such that their magnetic susceptibility is positive and their permeability very great compared with 1. If their temperature is lower than a threshold called the Curie temperature, they have permanent magnetization that disappears above this threshold. The Curie temperature of iron is 1,043 Kelvin.

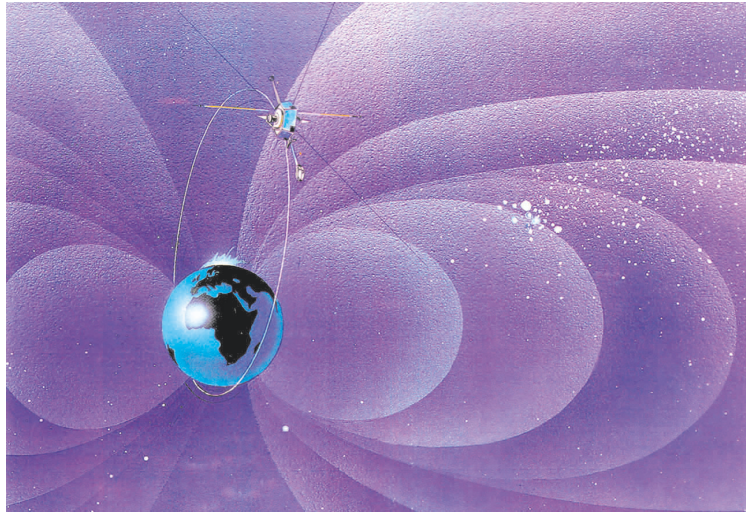


Figure 2.5 - An artist's impression of the magnetic field surrounding the Earth
The mission of the Swedish satellite, Viking, was to observe the environment of the Earth. It was launched in February 1986 (credit Viking, Swedish Space Agency).

According to some theories, the plasma river creates a magnetic field which, in turn, influences the surrounding charges, forcing them to turn and feed the field. It seems that once the magnetic field is in place it draws on its own resources in order to last. However, this theory provides no answer to the essential question concerning the origin of the planetary magnetic field. Other theories take into consideration the connection of the liquid nucleus to the solid mantle of the Earth and, in particular, the part that may be played by volcanoes. Unfortunately, as things stand, there is no theory that can explain at one and the same time the creation of a magnetic field on a planetary scale, its erratic reversals, the trend of irregularities of the field and its rapid fluctuations.

The inter and outer cores are heavier than the superficial layers of the Earth: accounting for 16% of the volume of the planet but carrying 33% of its mass. The Gutenberg discontinuity at – 2,900 kilometers indicates the point where the external core meets up with the solid mantle that extends to – 670 kilometers, then the outer shell and, finally, the lithosphere, the superficial layer.

Contrary to generally accepted ideas, the magnetic axis is not dependent on the axis of rotation of the planet but rather on the overall movement of plasma in the liquid external core⁴. At present, there is an angle of 11 degrees between the two axes and this changes continually.

⁴ In particular, this means that the Coriolis force that tends to align the axis of the magnetic dipole and the axis of rotation cannot in itself explain the overall movements of the liquid nucleus.

The magnetic field of the Earth is, at the first approximation, that of the dipole. It is directed from the South to the North of the Earth. The magnetic North Pole is at present in the North-Western territories of Canada.

Since the magnetic axis and the axis of rotation of the Earth are not aligned, it is also possible to develop a system of magnetic coordinates (figure 2.6). This is based on the system of geographical coordinates described previously: the meridians link the two magnetic poles, North and South. Each point of the magnetic equator is equidistant from these poles and the magnetic parallels are, of course, parallel. To guarantee the permanence of this system notwithstanding the occasionally irregular movement of the magnetic field, reference is made to a simple model of magnetic field that is close to reality: the dipolar field identical with that of a perfectly

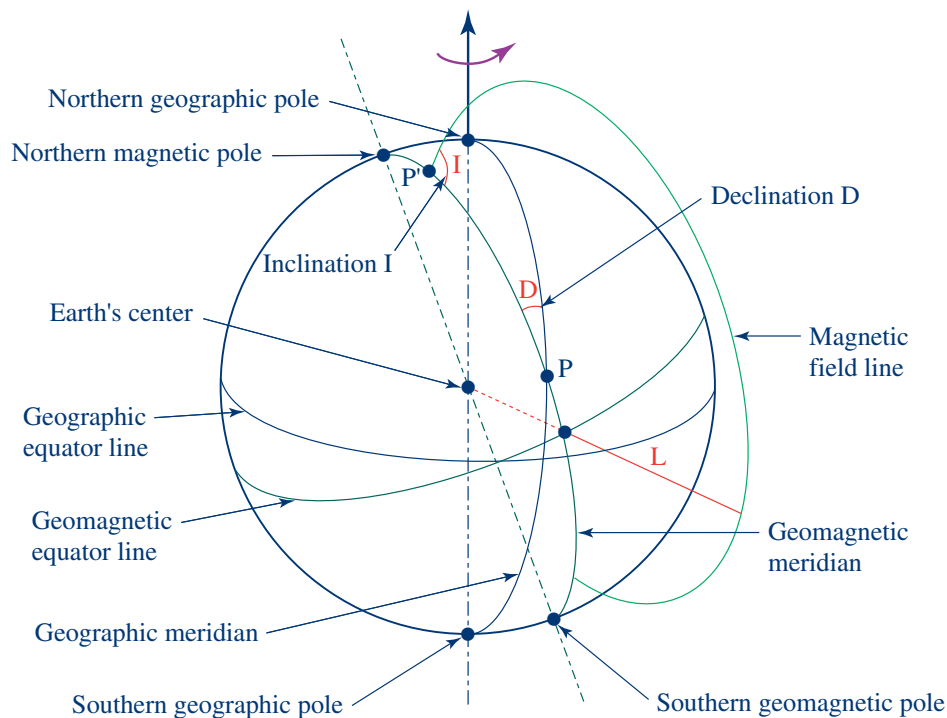


Figure 2.6 - The geomagnetic coordinates

Declination D (the angle between the geographical meridian and the horizontal direction of the magnetic field) and inclination I (the angle between the local field vector and the local horizontal plane) are represented by the red lines. With a view to making it easy to follow, the declination is represented by a point P on the terrestrial surface and the inclination by a separate point P'' . Obviously these two parameters can be determined jointly at one and the same point. L is the McIlwain parameter (the distance between the center of the Earth and the point where the magnetic field cuts the equatorial plane). These three parameters are covered in the text.

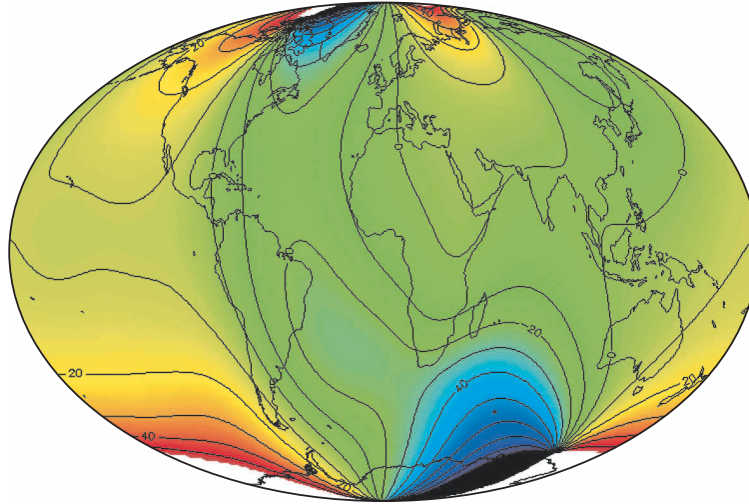


Figure 2.7 - Terrestrial declination in degrees averaged over the year 2000 and computed by an international model (IGRF) (credit NGDC-NOAA)

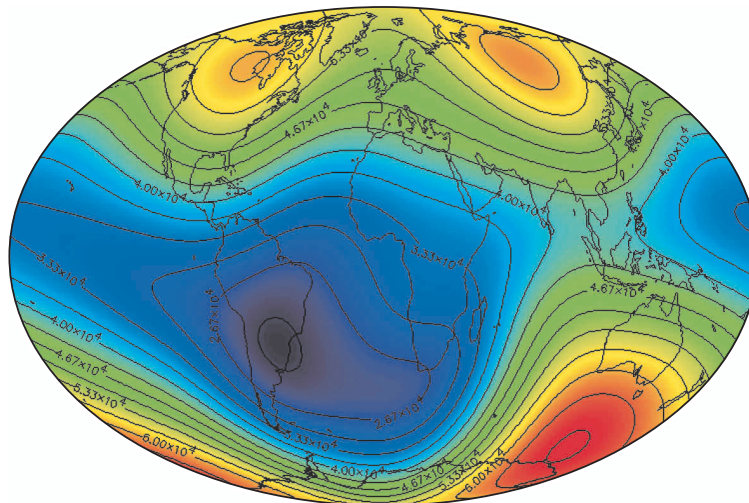


Figure 2.8 - The total magnetic field on the surface of the Earth, in nanoteslas, generated using an international model (IGRF)

This is an average over the year 2000. The red areas indicate a more intense magnetic field and the blue zones a lower magnetic field intensity (credit NGDC-NOAA).

homogenous magnet⁵. This system allows us to get our bearings in geomagnetic coordinates with a geomagnetic north pole and a geomagnetic south pole. However, for a precise study of the Earth, we need parameters that describe the field as it is

⁵ See appendix 4 for the expression of the dipole.

and not as represented by a dipole, using the true magnetic poles. The first parameter is the declination D . This is the angle formed by the geographical meridian and the horizontal component of the magnetic field, as shown in figure 2.6. In figure 2.7, the lines represent places where the declination is constant. They are every 10° . For instance, on line 0° a compass would indicate the precise geographic North Pole. Its shape is spectacularly irregular! The coordinates of the magnetic North Pole are 78.5 degrees North and 103.4 degrees West, near Ellef Ringnes island in Canada. The South Pole is at 65 degrees South and 139 degrees East, in Commonwealth Bay in the Antarctic.

The second parameter when defining the magnetic field in a given spot is inclination I . This is the angle between the local vector of the field and the local horizontal plane. In a way, it helps to define the skyward elevation of the field. A third parameter is helpful when defining the magnetic field. This is sometimes known as the McIlwain parameter which is shown conventionally as L on figure 2.6; this is the distance between the center of the Earth and the point where the magnetic field cuts the equatorial plane. For practical reasons, it is measured in units of terrestrial radius. Lastly, of course, we can measure the modulus of the magnetic field. It is higher at the poles where it amounts to about 70,000 nanoteslas (nT) than on the equator (33,000 nanoteslas on the magnetic equator). Figure 2.8 shows the modulus lines of the constant magnetic field on the surface of the Earth. In particular, it shows a distinct minimum in the magnetic field, in other words, a magnetic anomaly, in the south Atlantic (appendix 14 describes the magnetic indexes used to characterize the magnetic field of the Earth).

3. THE ATMOSPHERE OF THE EARTH

3.1. THE HOMOSPHERE

The atmosphere of the Earth is composed mainly of molecular nitrogen (78%) and molecular oxygen (21%). Classic meteorology covers the region between the surface and a mean altitude of 16 kilometers (about 17 kilometers at the equator and 8 at the poles). This layer is called the *troposphere*. The air is stirred continuously and this mixes its components.

The flux of solar energy that arrives perpendicularly to the Sun at one AU is 1366.1 W m^{-2} . However, to take into account the spherical shape of the Earth this value must be divided by 4 (i.e. 342 W m^{-2}) to obtain the overall mean amount of energy that reaches the Earth. 60% of this energy help to heat the surface and 40% are reflected or diffused by the surface toward space (the albedo is the ratio between the amount of energy reflected or diffused and the amount received. It approaches 1 for snow, for instance, and therefore amounts to 0.4 on average on the surface of the Earth).

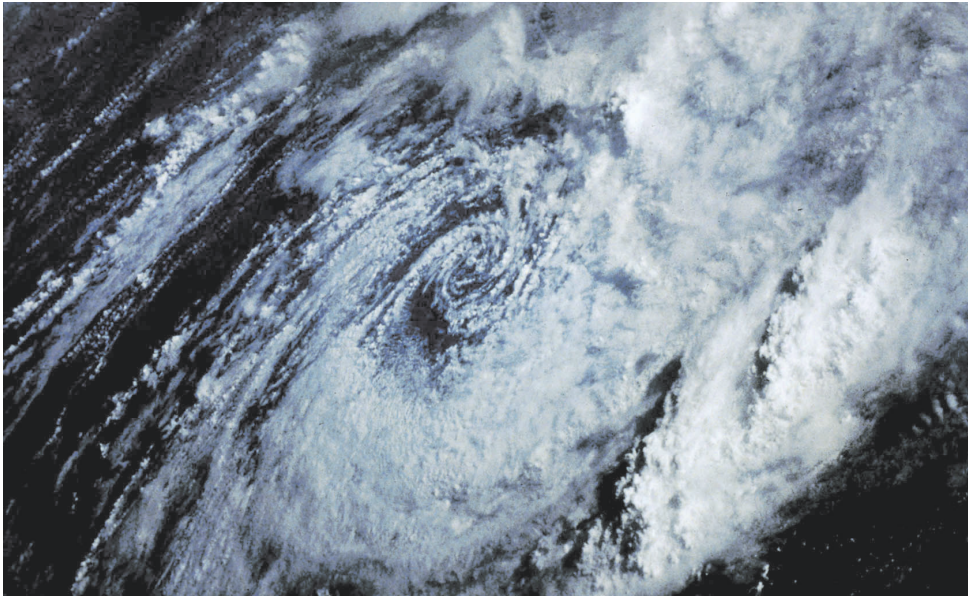


Figure 2.9 - The troposphere corresponds to a region in the atmosphere that is the subject of classic meteorology

It contains most of the water found in the atmosphere. Here we see an atmospheric depression (credit J.P. Haigneré, CNES).

The energy absorbed on the surface of the Earth heats the ground then, by conduction and convection the air on the lowest layer of the atmosphere. It also leads to considerable evaporation from the seas and lakes. This phenomenon, which is amplified by the transpiration of plants, results in a rate of relative humidity⁶ of more than 50% on average on the globe in the troposphere, which contains 99% of atmospheric water vapor.

Pressure and density decrease in function of altitude following an exponential law⁷. As we go upward, the temperature decreases in a linear manner in the troposphere, by 6 to 7 degrees per kilometer. The latter value depends greatly on the relative rate

6 Relative humidity, or the hygrometric degree, is a non-dimensional number. It expresses (usually as a percentage) the ratio between the partial pressure of water vapor in the atmosphere and the saturating vapor of water at the same temperature. A rate of 100% means that the air is saturated in water vapor.

7 This is the barometric law. It applies to both pressure and concentration and is written as follows

$$P(z) = P(z_0) e^{-\frac{z-z_0}{H}}$$

z_0 is a reference altitude, H is the scale height and is equivalent to

$$H = \frac{k_b T}{m g}$$

(m is the mean mass of the gas molecules, T their temperature, g the acceleration of the gravitation and k_b the Boltzmann constant). The barometric law is demonstrated in appendix 15.

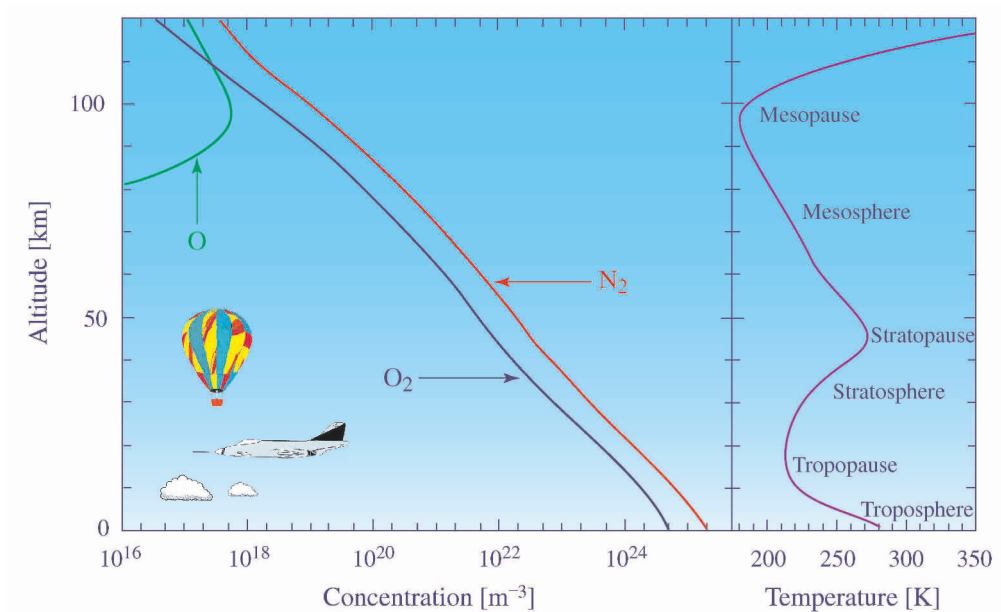
of humidity of the air, since, as it rises, the water vapor condenses and slows down the cooling of the air. The decrease therefore amounts to 9.8 degrees per kilometer when the air is completely dry and 5 degrees per kilometer for water-saturated air.

The above-mentioned laws are a reminder of the well-known fact: "hot air is lighter and rises". As it rises, it cools down, density increases and then it drops back down. This leads to the creation of convection cells that lead to instability. On the other hand, when the air is hotter at high altitudes than at lower ones, the medium is stable: the cold, heavier air stays at the bottom. This is the temperature reversal mechanism that sometimes covers the ground with a layer of mist in winter even though the Sun is shining a few meters above. This also helps explain the behavior of the following layer of the atmosphere.

Beyond the troposphere and up to an altitude of around 50 kilometers, the *stratosphere* is characterized by the progressive disappearance of water. The solar energy coming directly into the atmosphere or re-emitted by the ground is no longer used by condensation. It is largely used to warm up or dissociate molecules, especially ozone (it is most effective at around 40 kilometers) and molecular oxygen (most effective at 20-25 kilometers). The radiation responsible for the first dissociation (that of ozone) is between 240 and 310 nanometers and the second (oxygen) between 200 and 240 nanometers i.e. in the ultraviolet (see table of radiation in appendix 8). Due to its ability to filter ultraviolet the stratosphere allowed life to develop on the Earth. Unlike the troposphere immediately below it, the higher we rise into the stratosphere the higher its temperature. This is because the dissociation reactions are exothermic (they give off heat). The temperature then rises to around 0°C.

The upper limit of the stratosphere, about 50 kilometers up, is the *stratopause*. Above this, we enter the *mesosphere*. The concentration of ozone decreases, its dissociation, which gives off heat, is no longer a source of warming up, so as the altitude increases the temperature decreases. This occurs up to about 85 kilometers. The mesosphere is, as yet, a rather unknown part of our terrestrial atmosphere. It is too high to be able to measure its parameters with an observation balloon and too low for satellites to be used. Laser probes (LIDARS) and observation of its own specific radiation have been a help.

In all the "low" layers we have just described, molecules and atoms mingle, producing a homogenous gas. There is an atmospheric temperature and a concentration and these terms apply to the whole atmosphere. This is why the atmosphere is given the generic name of *homosphere* from ground level up to an altitude of 85 kilometers. The concentration is roughly 10^{25} particles per cubic meter at ground level and 10^{19} particles per cubic meter in the homopause, which is its upper limit. Pressure at ground level is around 1,015 hectopascals (hPa). This is still sometimes known as a pressure of one "atmosphere".



**Figure 2.10 - The vertical structure of the homosphere
obtained using model MSIS 95**

The beginning of April, on a calm day, toward noon, at a latitude of 45° North. To the left, we see the concentration lines ($[\text{m}^{-3}]$) of the principal components from ground level up to 120 kilometers (N_2 in red, O_2 in dark blue, O in green); on the right, the vertical temperature line ($[\text{K}]$) in function of altitude.

3.2. THE HETEROSPHERE, THE THERMOSPHERE, THE IONOSPHERE

The *heterosphere* begins above the homosphere. It only became possible to explore the properties of this part of the atmosphere with the advent of radio communications in the twentieth century. Subsequently, sophisticated radar techniques and measurements by satellite revealed a complex, dynamic medium, a gas consisting of a mixture of electrically-charged particles and neutral particles. This sheath still raises a great many questions about the part it plays in the eco-system of the Earth and in the emergence of life on Earth.

Space begins in the heterosphere, the lower legal limit of which is 80 kilometers. This is also where space weather really starts.

In the heterosphere, the concentration of molecules and atoms becomes very low and each component behaves as if it were alone. Here, the perfect gas behavior of the whole of the homosphere now applies separately to nitrogen, oxygen, and hydrogen, with a fundamental difference: each has its own scale height. The immediate result is a variation in their exponential concentration but with different

decrease rates⁸. This is shown in figure 2.11: at about 80 kilometers, molecular nitrogen is predominant, followed by molecular oxygen. About 250 kilometers higher up, atomic oxygen prevails. However, at around 1,000 kilometers, hydrogen becomes the most abundant element: since there is no longer a convection mixture, the heaviest elements stay in the lower layers and the lighter elements "float" above them.

One fundamental feature of the heterosphere is that it constitutes a filter for radiation in the extreme ultraviolet (EUV). As we have seen, the homosphere is quite effective at filtering some parts of the solar ultraviolet. However, the Sun also

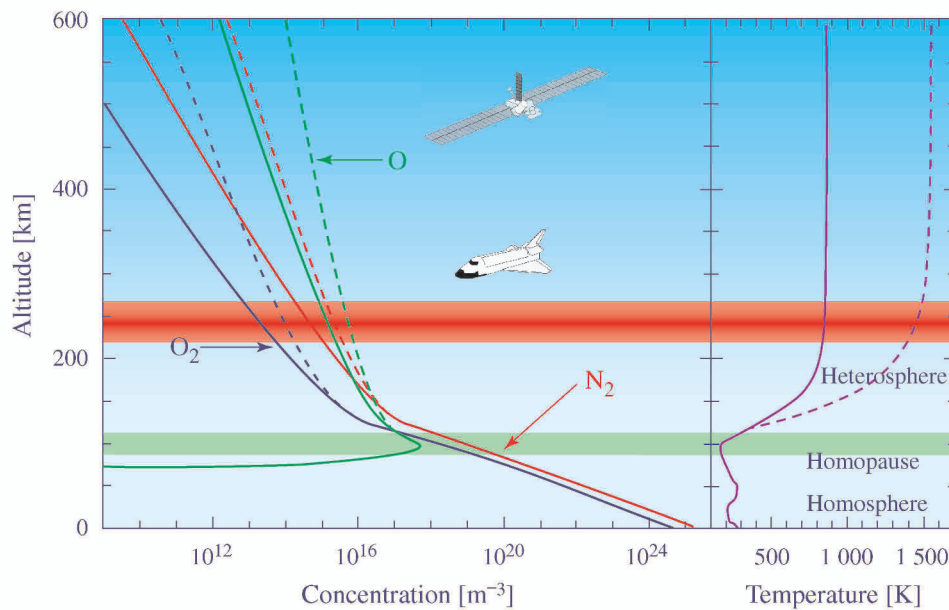


Figure 2.11 - The vertical structure of the atmosphere obtained by model MSIS 95

The beginning of April, on a calm day, toward noon, at a latitude of 45° North. To the left, we see the concentration lines ($[m^{-3}]$) of the principal components from ground level up to 120 kilometers (N_2 in red, O_2 in dark blue, O in green); on the right, the vertical temperature line ($[K]$) in function of altitude. The unbroken lines correspond to quiet solar activity ($f_{10.7} = 80$) and the dotted lines to high solar activity ($f_{10.7} = 300$). We can see that the homosphere is not affected by the change in activity. The green and red stripes represent the emission altitudes of the green and red lines of atomic oxygen.

8 The concentration of each gas varies according to a law in $e^{-\frac{z-z_0}{H_i}}$, H_i depending on gas i of mass m_i : $H_i = \frac{k_b T}{m_i g}$.

emits radiation with an energy of more than about ten electronvolts and this is strongly correlated to solar activity. If this radiation reached the surface of the Earth, it would prevent all forms of life from developing. How is it filtered? In three specific ways. Firstly, by ionization: the radiation tears a peripheral electron away from the atoms and molecules it hits, creating an electron and an ion. Secondly, by excitation: as it absorbs radiation, the atom or the molecule accelerates and warms up, the molecule vibrates and rotates and the energy level of the electrons inside changes. The third way in which radiation can be absorbed is by dissociation; this breaks a molecule up into several parts.

Fortunately, the upper atmosphere undergoes these phenomena⁹ and prevents the extreme ultraviolet from stretching down lower than an altitude of about 80 kilometers. The atmosphere is partially ionized.

At lower altitudes, in the troposphere for instance, if a phenomenon such as a flash of lightning creates ions and electrons, they immediately recombine to form atoms and molecules. This is because the atmosphere is dense and they cannot travel very far, only a matter of a few millimeters, before coming into contact with a new particle. However, this is not the case above about 80 kilometers where the atmosphere is so tenuous (see figure 2.11) that ions and electrons can travel over huge distances such as 10 kilometers at an altitude of 200 kilometers, before coming into contact with an atom, a molecule or another ion.

Here we are in a medium that is very different from the matter with which we are familiar, a mixture of neutral gas, ions that are more or less energized and electrons. The neutral gas has been given the name of *thermosphere*. The combination of ionized gas, ions and electrons is the *ionosphere*. This combination is a *plasma* called atmospheric plasma. Its properties are quite different from those of a classic gas consisting of neutral particles, since the movement of the charged particles is sensitive to the electrical and magnetic fields. However the proportion of charged particles remains low in comparison with that of the neutral particles: about one billionth at an altitude of 100 kilometers and one tenth at around 1,000 kilometers. The properties of the atmospheric plasma are also very different from those of low altitude atmosphere. They are indeed very closely correlated to solar radiation in the extreme ultra-violet and therefore to solar activity. When the Sun is in a quiet period, the temperature of the ions and electrons created as they absorb the energy of the photons may seem high: about 1,000 Kelvin for ions at 400 kilometers and 1,500 Kelvin for electrons. However, these are low values compared with those that

9 The ionization thresholds i.e. the thresholds required to tear a peripheral electron away from the atoms and molecules are respectively 12.1 electronvolts for O₂, 13.1 electronvolts for O and 15.58 electronvolts for N₂. The excitation thresholds are much lower. For one of the most considerable excitations in the atmosphere, that of the fine structure of oxygen, the threshold is 0.5 electronvolts.

occur when the Sun is in a particularly active period: the temperature of the ions can then be as high as 3,000 Kelvin and that of the electrons 9,000 Kelvin at the same altitude of 400 kilometers. On one and the same day, very significant variations can be observed, as shown in figure 2.12: at 400 kilometers the electron concentration increases two-fold between 6 a.m. and 12 noon and there are variations of more than 100 Kelvin on the electron and ion temperatures...

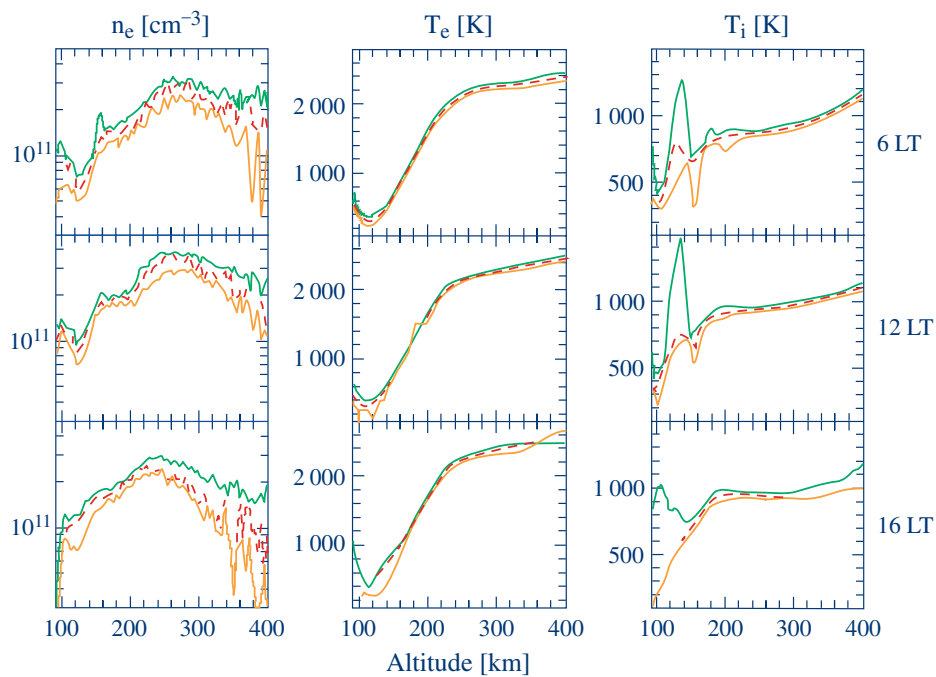


Figure 2.12 - Typical variations in electron concentration (n_e), electron temperature (T_e) and ion temperature (T_i) (measured by the EISCAT radar in Tromsø, Norway) in function of altitude at different times on the same day

June 1994. At that time of year, the Sun always lights the atmosphere at this latitude, North of the polar circle. Local times are given to the right of the curves. At 6.00 LT, the maximum of F region is at approximately 280 kilometers dropping to about 240 kilometers as the Sun lights up the lower layers of the atmosphere. E region that is very pronounced at the end of the night fills up little by little during the day. The Sun was active on that day, leading to high temperatures: more than 2,500 Kelvin at 400 kilometers for the electrons and between 1,000 and 1,500 for the ions. The dotted lines show the contours at the precise times indicated and the unbroken lines show the minimums and maximums 30 minutes before and after these times, providing an indication as to the variability of the ionosphere. Ion temperature, which is very sensitive to the presence of electric fields in E region, shows a variation of several hundred Kelvin.

Table 2.2 - Typical parameters of the atmospheric layers

Altitude [km]	75	100	150	200	400	800	1,200	3,000
"Layer"	D	E	F ₁	F ₂		F sup		
n_n [m ⁻³]	10 ²¹	10 ¹⁸	5 × 10 ¹⁶	8 × 10 ¹⁵	10 ¹⁴	10 ¹²	2 × 10 ¹¹	10 ¹⁰
n_e/n_n	10 ⁻¹²	3 × 10 ⁻⁹	4 × 10 ⁻⁶	10 ⁻⁴	4 × 10 ⁻³	4 × 10 ⁻²	10 ⁻¹	1
T_e	200	200	700	1,500	2,500	3,000	3,200	3,500
T_i	200	200	600	800	1,000	2,500	3,000	3,400

n_n is the neutral concentration (thermosphere), n_e the electronic concentration (ionosphere), T_e and T_i the electronic and ionic temperatures.

The manner in which the ionosphere is designated tells the story of its discovery, during the first years of the conquest of space:

- ♦ D region below 80 kilometers, where negative ions prevail;
- ♦ E region between 85 and 150 kilometers, where positive molecular ions are in the majority (mainly O₂⁺ and NO⁺);
- ♦ F₁ region between 150 and 200 kilometers, where there is a transition between the molecular ions (primarily NO⁺) and the positive atomic ions (mainly O⁺);
- ♦ F₂ region where ion O⁺ is the principal ionic type, characterized by the transition between photochemical mechanisms (in the lower part) and diffusion mechanisms (in the upper part);
- ♦ the high ionosphere where ion H⁺ prevails after its creation through the exchange of charge with ion O⁺ then its diffusion.

The origin of these ionized layers is essentially due to the solar radiation of the most energetic photons. However, another source of sporadic ionization, mainly at an altitude of between 90 and 125 kilometers (and, to a lesser degree, up to 300 kilometers) can be found on both the day side and the night side of the Earth: meteorites. They are heated as they enter the atmosphere and bring with them sufficient energy to ionize the gas. Higher up, the number of molecules is not sufficient for friction to be significant. At a lower altitude, chemical recombination occurs too rapidly for the life span of the electrons and ions to have any repercussions. This is why the influence of meteorites is felt mainly in E region. This effect can add between and 100 and 1,000 electrons per cubic centimeter to the ionosphere, creating magnesium ions that are not found in an ionosphere ionized only by photons.

We have indicated that electromagnetic radiation in the extreme ultraviolet can be absorbed by ionization but also by other phenomena: dissociation, excitation, heating. All these phenomena compete if the energy of the photons exceeds the ionization thresholds. When the energy is below these thresholds, less than about a

dozen electronvolts or, in terms of wave-length, lower than about 100 nanometers¹⁰ radiation is also abundant and has a considerable effect on the thermosphere.

Its effectiveness in the phenomenon of dissociation is at a maximum at between 100 and 110 kilometers. In particular, the radiation dissociates molecular oxygen into atomic oxygen which then spreads to the lower altitudes.

The electromagnetic radiation also excites thermospheric atoms and molecules which sooner or later revert to their state of equilibrium. This can be brought about by chemical recombination. It is often achieved by the emission of one or sometimes two photons in the ultraviolet, the near infrared and even the visible. Oxygen, in particular, has two intense signatures, one in the green, at an altitude of around 100 kilometers and one in the red, at about 250 kilometers. These rays are difficult to see in a nocturnal sky since they are of low intensity compared with visible solar radiation. However, sighting on the limb¹¹ shows them up as magnificent luminous shells above our planet.

We have seen the phenomena of ionization, dissociation and excitation. The fourth way in which the high atmosphere absorbs the electromagnetic radiation of the Sun is by heating. So it is not surprising that temperature variation in the thermosphere is closely linked to solar radiation.

The source of the heat is indirect: the temperature of the atmosphere is increased by the friction of energized particles against those that have not been energized and by chemical reactions, not by direct interaction between the atmosphere and solar radiation. The temperature rises considerably above the mesosphere, roughly 8 to 10 degrees per kilometer between 100 and 150 kilometers (see figure 2.11). This is a positive temperature gradient: hot air no longer rises since it is already on top. Convection is inhibited and only conduction can transfer energy from one layer to the next.

This heating is effective as far as 200-300 kilometers up; above this altitude the atmosphere is too thin to conduct heat. Higher up, the temperature becomes constant (see figure 2.11) and is then called exospheric temperature T_{∞} . Its typical value is between 1,000 and 1,200 Kelvin during a quiet period but it can exceed 2,000 Kelvin during an active period. This explains why this part of the atmosphere is called the thermosphere.

10 According to the formulae given in the first chapter, energy E can be converted into temperature and in the case of kinetic energy alone, excluding internal or chemical energy for example, into velocity. Let us remember that a particle of energy of 0.1 electronvolts corresponds to a temperature of 1,100 Kelvin. Furthermore, the energy of a radiation is characterized by a wavelength. Radiation with a wavelength of less than or equal to 100 nanometers (extreme ultraviolet) has an energy of more than about 12.4 electronvolts.

11 The luminous edge of the disk of an astronomical object (illustrated by figures 2.13 and 2.14).

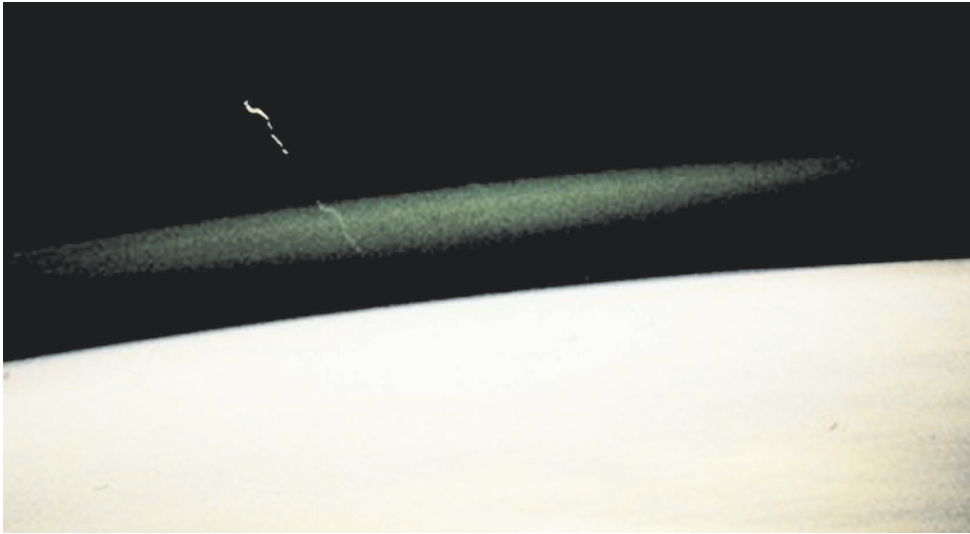


Figure 2.13 - At an altitude of about 110 kilometers, the green line shines above the Earth (which, in contrast, appears very light and luminous), taken by the cosmonauts on board the Soviet station Saliout 6 in 1978 (credit S. Koutchmy, IAP-CNRS)

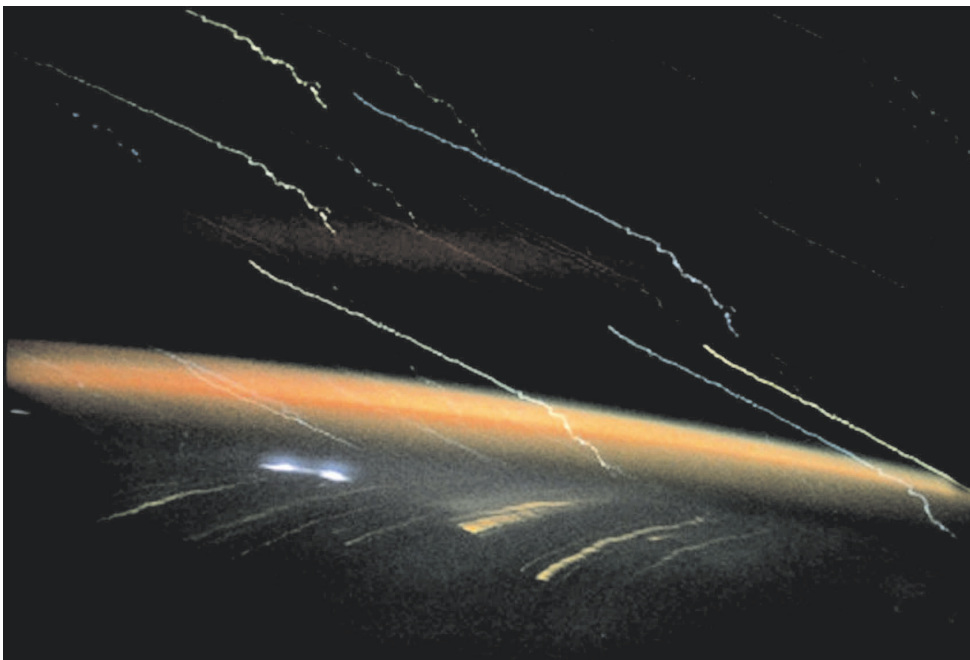


Figure 2.14 - Emission of the red line at an altitude of about 250 kilometers, taken from the Soviet station Saliout 6 in 1978
The blue and white lines are stars that seem to be trooping past during the shot. At the bottom, the limb of the Earth (credit S. Koutchmy, IAP-CNRS).

The four effects of solar radiation on the high atmosphere –ionization, dissociation, excitation, heating– depend on the intensity of the radiation and therefore on solar activity. A sudden surge of energetic photons, following a solar flare, for instance, leads to an increase in the ion and electron concentrations and in the warming up of the thermosphere, which results in the dilatation of atmospheric gas. The ions and the electrons recombine chemically, either between themselves or with neutral atoms and molecules. These reactions are rapid and balance out production so that, on the night side, the ionosphere empties suddenly and almost completely. Oddly, on the day side, at an altitude of about 150 kilometers, this chemistry gives rise to a predominance of the nitrogen oxide ion, whereas there is practically no neutral nitrogen oxide, which is its closest of kin.

4. THE MAGNETOSPHERE

Can we still talk about the atmosphere of the Earth when, beyond an altitude of about 600 kilometers and up to several terrestrial radii, particle concentration becomes so low that their behavior is no longer a function of collisions but is a consequence of the configuration of the magnetic field? This is all the more true as the altitude increases. Although there is no legal limit to the atmosphere, the nature of the environment changes and becomes the *magnetosphere*.

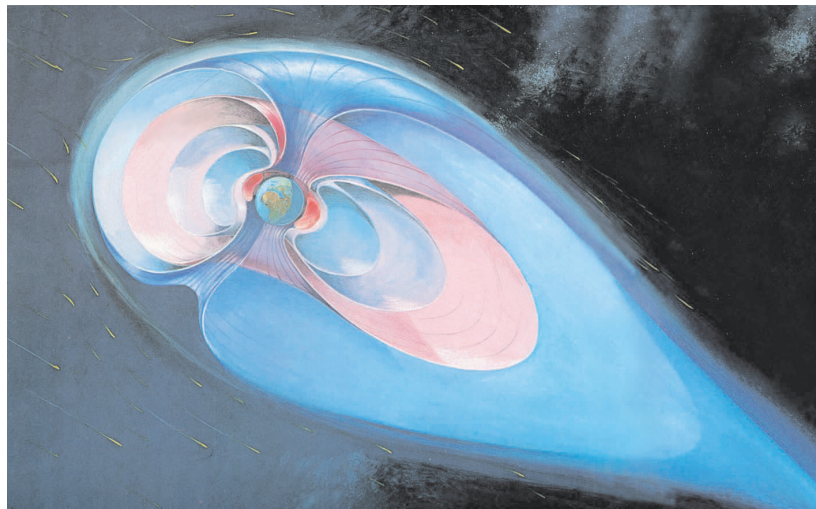


Figure 2.15 - An artist's impression of the magnetosphere

The Sun sits on top left and the solar wind is represented by yellow particles moving through space. The magnetosphere surrounds the Earth with various characteristic zones, identified here by color (in actual fact, photographs taken in visible light show no cavity of this type). In this three-dimensional representation, the magnetic field lines become areas known as magnetic shells (credit Solar Publishing).

Figure 2.15 is a representation of the magnetosphere, with colors that show up some of its characteristic zones. The difference compared with figure 2.5 which shows the field lines near our planet is spectacular, not to say disconcerting. This is not only because of the three-dimensional magnetic shells instead of two dimensional field lines but also because of the stream-lined shape with embedded sectors with apparently clearly identified boundaries. These strange characteristics are the result of complex interaction between the magnetic field of the Earth and the solar wind.

Remember that electrons and protons are released continuously from the seething surface of the Sun and that solar activity governs the sporadic ejection of additional ions and electrons, along with an avalanche of radiation, particularly in the ultraviolet. On June 3rd 1999, for instance, the THEMIS telescope was able to observe a flare that was triggered simultaneously in less than one 25th of a second on several sites a few thousand to 100,000 kilometers apart¹². Coronal mass ejections may be closely connected to flares but this is not systematic.

The solar wind and the geomagnetic field interact in various ways. One is described in terms of both magnetic pressure (of the Earth's field) and kinetic pressure (of the solar wind). Furthermore, the magnetic field influences the charged particles of the solar wind.

For a start, a magnetic field forces electrical charges to trace a spiraling movement around its field lines, in a direction that depends on the sign of the charge. Another effect is triggered when the charged particles have an initial speed as they enter a magnetic field. They then undergo a force that separates the positive and negative charges and this in turn gives rise to an electrical field that tends to push them closer to each other. So when interactivity is triggered between the solar wind and a variable geomagnetic field, this is enough to create an environment that is no longer only magnetic but also electromagnetic.

The flux of charged particles is characterized by the density of the electric current. By definition, it is proportional to the difference between the flux of the positive charges and that of the negative charges¹³. It is orientated in the direction of the speed of the ions. When the ions are preponderant, it is said to be carried by the ions. Obviously, it is carried by the electrons if they are more abundant but in this case it flows in the opposite direction to that of the electronic speed. By agreement,

12 In such a short time, the effect of an eruptive site has not has time to propagate to trigger another eruption. Light itself, the speed of which is an insurmountable upper limit, travels 75,000 kilometers in 1/25th of a second. This means that these eruptions in the photosphere had a common cause.

13 In a mixture of charged particles of species s characterized by mean flow velocities $\vec{v}_s$ and concentrations n_s the current density $\vec{j}$ in the local reference system is written: $\vec{j} = \sum_s q_s n_s \vec{v}_s$ where q_s represents the charge of species s (see appendix 4).

it is written $\vec{j}$. Although by agreement an electric field is always directed from the positive charges toward the negative charges, a current density can have any direction. The electric current passing through any surface is the integral sum of all the currents passing through that surface.

The physics of these phenomena (a spiral around a field line, the separation of charges or the creation of an electric current) is described in appendix 17. To describe the magnetosphere, one only has to admit that all these phenomena co-exist that to an extent that differs according to the spot under observation. The magnetosphere can therefore be described as a complex system of electric currents which have a decisive impact on our modern technology: satellites, telecommunications, positioning systems and so on.

4.1. THE MAGNETOSPHERE AND THE NETWORK OF CURRENTS

The slow wind covers the distance between the Earth and the Sun in 3 days whereas the fast wind takes only ten hours and electromagnetic radiation 8 minutes. As they near the Earth, electrically charged particles are exposed to an increasing geomagnetic field. This gives rise to a force which is perpendicular to both the wind and the field (the Lorentz force) which deflects the ions towards the afternoon side of the Earth (East) and the electrons towards the morning side. The distance at which

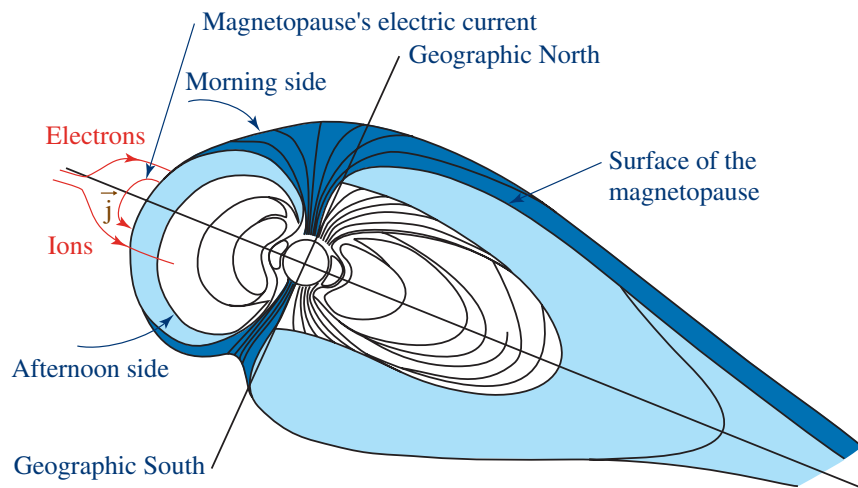


Figure 2.16 - The solar wind skirts round the Earth, creating a protective area, the magnetosphere (shown here in blue)

The ions are moving toward the evening side, to the front of the page, and the electrons toward the morning side, to the back of the page. This separation of charges near the Earth triggers the magnetosphere current, represented by the red arrow.

this interaction takes place is that at which the kinetic pressure of the solar wind offsets the magnetic pressure of the terrestrial field¹⁴. The Earth is protected by a magnetic sheath along which the solar wind flows: the *magnetopause* (figure 2.16).

The front of the magnetopause is at approximately ten terrestrial radii from the surface of the planet. However, this distance is closer to thirteen terrestrial radii when solar activity is at a minimum and six during active periods (flares, eruptions, coronal mass ejections); on its flanks, the magnetopause is at about fifteen terrestrial radii from the Earth. On the night side, it is shaped like the tail of a comet. On the outside, the space is subjected to the solar wind and the interplanetary magnetic field. Inside –in the *magnetosphere*– the magnetic field of the Earth is the controlling force. The magnetopause stands like a barrier between the two.

The separation of the solar wind charges on the day side gives rise to a first current known as the magnetopause current; this is the reverse motion of the ions (toward the front of the page on figure 2.16) and the electrons (toward the back of the page on the same figure).

Let us imagine that we are standing upstream from the magnetosphere, on the axis between the Earth and the Sun. Particles are arriving continuously from the Sun at an average velocity of 370 km s^{-1} ; this corresponds to energy of about one tenth of an electronvolt for the electrons or one hundred electronvolts for the ions. In the magnetosphere, this speed decreases in the Sun-Earth direction whilst the particles are accelerated perpendicularly to this axis, i.e. in an East-West direction. Between approximately twelve and fourteen terrestrial radii, a zone of compression of matter is created; impacts are more numerous here because the fast particles hit the lower particles in the direction of the Earth. The solar wind warms up (figure 2.17). Due to these collisions, the protons and the electrons pick up a considerable amount of energy: soon, it is no longer expressed in tens of electronvolts but in thousands of electronvolts. The particles that skirt round the Earth and form the magnetopause are, therefore, extremely rapid.

On the night side, the magnetopause closes in to several tens of terrestrial radii and takes the form of the blue shell in figure 2.15. On this drawing, we can see far more than the magnetosphere itself: we can make out its internal structure. This three-dimensional representation clearly shows that the magnetic field lines are veritable magnetic shells. The drawing uses colors to distinguish them. This is simply to enable us to distinguish the different zones which are of interest to us: polar cusps, auroral ovals, the plasmasphere, radiation belts... Each of these zones has its own characteristics due to the various phenomena triggered by the Sun and plays a specific part in space weather.

14 The computation carried out in appendix 18 shows that the position of the magnetopause on the front of the magnetosphere is about 12.5 terrestrial radii away.

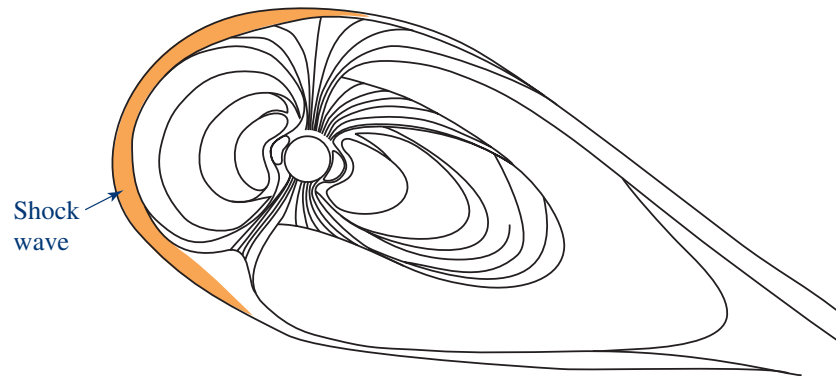


Figure 2.17 - Upstream from the Earth, the shock wave (shown here in orange) creates a warming up of the solar wind, which then accelerates before traveling along the magnetopause

Before going on to describe them, let us consider the scale of the astronomical objects that interact. The diameter of the Sun is 109 times that of the Earth. This implies that the solar wind does not merely strike the front of the magnetosphere but also moves along its East-West flanks or its North-South boundaries. The particles that are blasted out from the Sun and cross the orbit of the Earth have different fates and, therefore, interact in different ways with our planet. To avoid losing our way through the various paths and phenomena, let us follow the tracks of some specific families of particles.

Let us first take a look at the family of particles that comes into contact with the geomagnetic field in the Earth-Sun axis (figure 2.18). Two phenomena are to be noticed: the heating and separation of charges due to the deflection of ions toward the evening side and of electrons toward the morning side. However, their paths cannot simply be directed East-West, since other particles arrive in a continuous flux from the Sun. This explains why the ions (on the evening side) and the electrons (on the morning side) recapture a movement toward the night side of the Earth. As they move along the magnetopause, they cool down progressively until they revert to their initial characteristics at 100 to 200 terrestrial radii, far away from the night side.

What types of particles can be found on the flanks of the magnetosphere? A mixture of globally neutral solar wind coming directly from the Sun and particles that have been accelerated on the front of the magnetosphere, with charges that are distributed to the East and the West of the magnetosphere. The magnetopause barrier is not a completely impervious boundary for all these particles: between 5% and 10% of them pass through it, both at the front and on the flanks, while most of them head for interplanetary space. At a distance of 100 to 200 terrestrial radii, the effect of the geomagnetic field is no longer sufficiently intense to prevent solar wind particles arriving from the East, West, North or South meeting up at a *reconnection* site. Impacts and collisions provide particles with further means of entry into the

magnetosphere. It is because of these entrances that the magnetospheric cavity contains a (low) number of the ions and electrons that, a few hours to a few days earlier, were being blasted off the Sun.

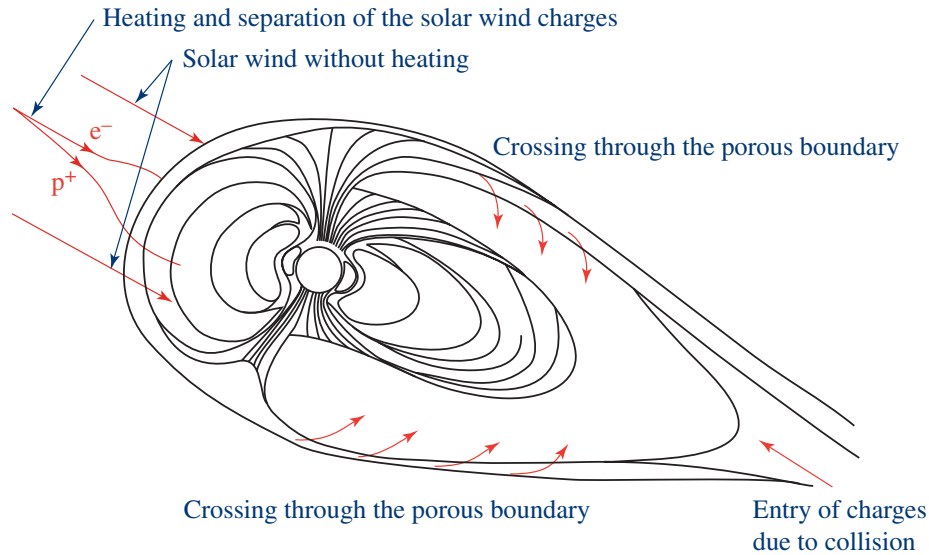


Figure 2.18 - Solar wind particles enter the magnetosphere

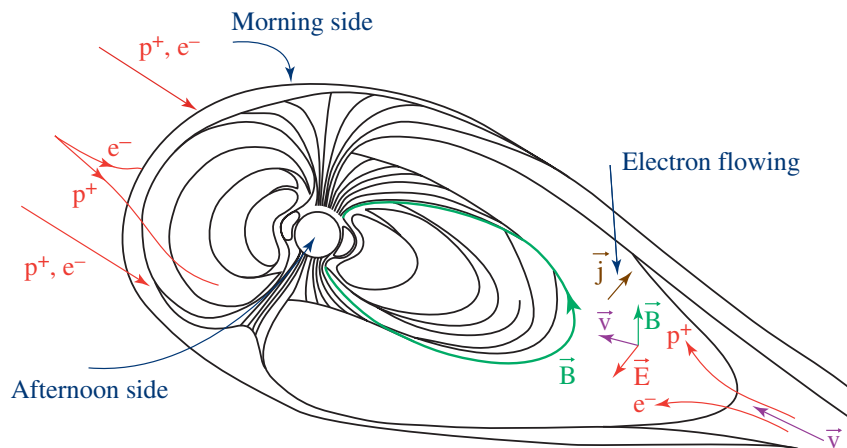


Figure 2.19 - The creation of the electric field $\vec{E}$ and of a current $\vec{j}$ crossing the magnetosphere

The particles of the solar wind that have reached the front of the magnetosphere have undergone a separation of charge (p^+ means protons and e^- electrons). Inside the magnetosphere, ions are attracted to the morning side and ions to the evening side but they all undergo a force under the combined influences of the magnetic field and the geomagnetic field $\vec{B}$. They are compelled to move toward the Earth (velocity $\vec{v}$).

Once this small cluster of particles has passed through into the magnetosphere, it is protected from the solar wind and is now only subjected to the electromagnetic forces. The ions head for the boundary on the day side, attracted by the flux of electrons flowing on its external flank. The internal electrons make for the boundary on the evening side. Seen from the outside, neutrality is respected. However, as seen from the inside of the magnetosphere, there is an electric field between the positively charged particles and the internal electrons of the magnetosphere. This field runs across the entire magnetosphere, from the morning side to the evening side (figure 2.19). It fills the whole magnetosphere, from the tail to the front of the Earth. It can vary in intensity extremely rapidly, since the solar wind is a mixture of fast wind and slow wind pushing each other around. So it is hardly surprising that the flux of particles at a given point in the magnetosphere changes from one minute to the next, leading to variations in the electric field inside the magnetosphere.

These variations have an immediate effect on the shape of the magnetopause. The first measurements taken by the constellation of CLUSTER satellites in 2001, showed that the magnetopause is not the smooth surface shown in our figures. The magnetosphere dilates when the solar wind is not very intense and contracts when it increases. These phases of dilatation and contraction occur so rapidly that the magnetopause resembles a rippled surface. The ripples have an amplitude of several thousand kilometers and move at a speed of several hundred kilometers per second, like a huge swell on a magnetic sea.

A small part of the solar wind enters the magnetosphere. Particles still flow along its flanks but through these the effects of the South-North geomagnetic field and the electric field directed from the morning side toward the evening side join forces to influence the charged particles. They subject them to a movement that sends them heading toward the Earth (see figure 2.19). It is to be noted that this compulsory movement is given regardless of the sign of the charge (see appendix 17); it affects all the particles, whether they are ions or electrons. They undergo its influence in the plane of the magnetic equator but over a great depth of approximately three to seven terrestrial radii. This area is called the *plasma sheet* (figure 2.20). On the night side of the Earth, the near boundary is at about seven terrestrial radii. Far out into space, it links up with the magnetopause at a distance of between 100 and 200 terrestrial radii; this distance is sometimes considered to be the end of the terrestrial magnetosphere. The energy of the ions found in the sheet is typically between 2 and 5 kiloelectronvolts and that of the electrons 0.5 to 1 kiloelectronvolts. The plasma sheet is the most dynamic part of the magnetosphere. Mean density in the sheet is between 3×10^5 and 5×10^5 particles per cubic meter, which is in stark contrast to its northern and southern neighborhoods: outside the sheet, there are only about 1,000 ions per cubic meter. This is the lowest concentration of particles in the terrestrial environment (the best vacuum, according to physicists).

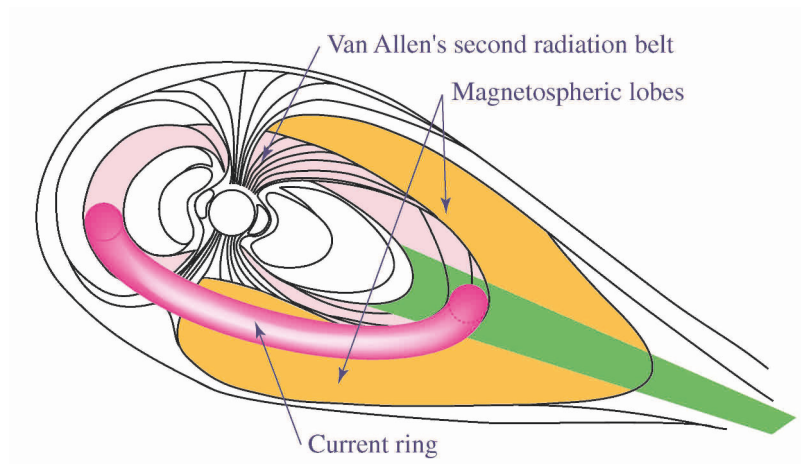


Figure 2.20 - The plasma sheet and a Van Allen belt

We have shown the plasma sheet in green. The yellow areas are called magnetospheric lobes and are the regions with the greatest vacuum in the terrestrial environment. When the particles of the sheet can no longer progress toward the Earth because the magnetic field is too intense, they skirt round it, outlining a current ring. Particles break away from this ring and fill the pink shell, known as "Van Allen's second radiation belt".

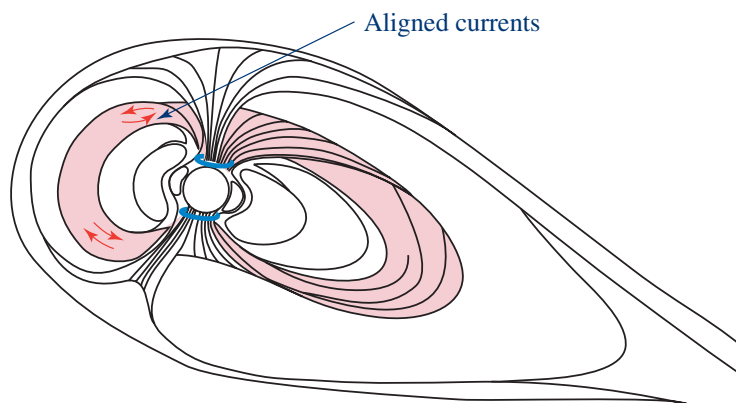


Figure 2.21 - Here again we have the pink shell of figure 2.20

The arrows represent the aligned currents but they could equally well represent the path of ions or electrons. The feet of the shell outline two ovals (shown here in dark blue) in the high terrestrial atmosphere.

As they near our planet, the charged particles encounter an increasingly intense magnetic field. This configuration calls to mind the one described previously when the solar wind approached the Earth on the day side, after being blown off the Sun. The major difference is that we are now inside the magnetosphere and not on the outside. Since the same causes produce the same effects, as the field intensifies inside the magnetosphere, the charges separate, creating a current. This strengthens

the current described previously (see figure 2.19) due solely to the presence of the electric field. Total current arising from both the electric field and the interaction of the magnetic field is called the *cross-tail current*.

In the same way as on the day side solar wind was halted by the pressure of the magnetic field, in turn, particles inside the magnetosphere end up being stopped, typically at between two and ten terrestrial radii, by a magnetic field so intense that they can no longer move forward. So then what happens to these ions and electrons? They skirt the Earth, at a respectable distance, creating a *ring of current* (see figures 2.20 and 2.21) that surrounds the Earth at low latitudes. This ring is typically at between four and seven terrestrial radii. Current density is about 10^8 A m^{-2} for particles, 90% of which have energies of between 10 and 250 kiloelectronvolts. Its influence at Earth level is particularly noticeable at low latitudes, toward the equator.

This encircling of the Earth is not, however, the only motion to which these particles are subjected. They travel at a distance from the Earth that is roughly constant and stay within zones with a constant magnetic field. We can see in figure 2.20 that they are confined within a magnetic shell i.e. a volume defined by closed field lines. Those that have an initial North-South velocity or those that pick one up following collisions, spiral around the local field line and leave the ring to explore the magnetic field shell. As they near the Earth, most of these particles bounce off the atmosphere¹⁵ and turn back toward the other hemisphere, tirelessly traveling to and fro in their magnetic shell. At any given time, only a few of the particles find their way into the terrestrial atmosphere but, sooner or later, they find a way in.

The Earth is, therefore, surrounded, inside the magnetosphere, by a volume filled with energetic particles crossing from North to South and back until, at the mercy of the collisions, they can enter the atmosphere and be absorbed in it. This zone in which particles are stored has been given the name of the second Van Allen belt, after the person who discovered its existence, or external radiation belt (in pink on figures 2.20 and 2.21). The outer radiation belt and the current ring are, therefore, two manifestations of the same particles that arrive in the magnetosphere from the solar wind and draw nearer to the Earth in the plasma sheet. The rings plotted by the feet of the external belt are at high latitudes, between 65° North or South, above Lapland, Nunavut, Baffin Island, Siberia, Alaska, Ross Island, Terre Adélie... They are called the auroral ovals and are shown in blue on figure 2.21.

The particles that travel along the Van Allen Belt are also affected by the electric field that flows through the whole of the magnetosphere. Under its influence,

15 Strictly speaking, it is a magnetic reflection: the magnetic field becomes increasingly intense as it nears the Earth and, particularly, increasingly dense. The field lines close in. The particles tend to slow down and can even come to a halt in their race toward the Earth, at altitudes that often exceed several thousand kilometers. This stopping point is the magnetic mirror point. The physics of these phenomena are explained in appendix 17.

combined with that of the magnetic field, they undergo charge separations throughout their path and once again these generate electric currents. Since they occur along the magnetic field lines, they are called *field-aligned currents*. They reach a few hundred kilometers down into the atmosphere of the Earth. From interplanetary space the particles of solar wind have crossed through the magnetosphere and have come back toward Earth generating various electric currents along their path: magnetopause currents, cross-tail currents, first in the form of rings and then in lines. They trigger electric fields and these in turn draw the ions and electrons into a convection system that affects the thermosphere above the polar ice caps.

Let us leave this region aside for a while and take a look at other areas of the magnetosphere, on this side of the internal limit of the plasma sheet, five to six terrestrial radii from the surface of the Earth, so near to it that whatever the latitude the very thin atmosphere is carried along by the rotation of the planet; this is known as "corotation". This area, in blue on figure 2.22, is called the *plasmasphere*. Here the concentration varies between 10 billion particles per cubic meter (10^{10} m^{-3}) at the top of the ionosphere, at approximately 1,000 kilometers, and 100 billion (10^8 m^{-3}) at its outer boundary, the *plasmaopause*. Immediately beyond this, in the external radiation belt, density drops by factor 10. However, the energy of the particles in the plasmasphere is lower than that of the radiation belt, less than 1 electronvolt on average.

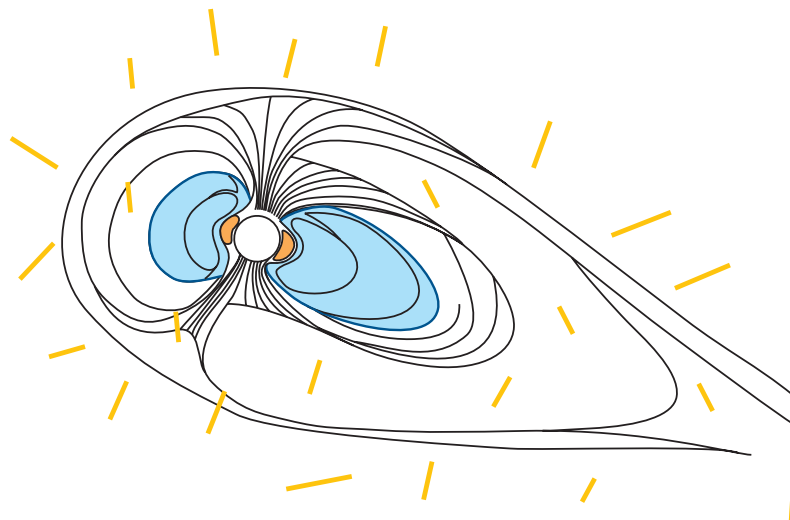


Figure 2.22 - The position of the plasmasphere, in pale blue, and of the plasmaopause (dark blue line)

The plasmasphere is carried along by the rotation of the Earth. Inside the plasmasphere and also co-rotating with the Earth is the internal radiation belt, identified in orange. The yellow lines represent particles due to the cosmic ray (stellar wind) that propagates in all directions in space.

Inside the plasmasphere there is another radiation belt, the first Van Allen belt, or inner belt. It is in a compact region centered above the equator, at an altitude of a few thousand kilometers. This is shown in orange in figure 2.22. It is very different from all that has been described previously. This is because the origin of the belt is not to be found in the solar wind but primarily in the ionization triggered by cosmic rays. In spite of its name, which is misleading, cosmic radiation is made up of particles and not electromagnetic radiation. It is simply stellar wind, from stars other than the Sun. Since they are a very long way off, the wind arrives on Earth made up of electrons and highly energetic ions, the others having been absorbed near the emitting star. Energies range from a few tens to several hundred megaelectronvolts. How does this stellar wind give rise to a radiation belt? This is what happens: the stellar wind, in the form of particles (protons, electrons) is so energetic that it has no problem entering the first the magnetosphere and then the atmosphere, where it collides with the atoms of oxygen and nitrogen to produce neutrons. The latter are not affected by the magnetic field and escape from the collision zone with high energies (more than 10 megaelectronvolts). However, a neutron is unstable and has a limited life span (about 15 minutes in its own reference frame); it then dissociates to give way to a proton and an electron. The protons formed in this way travel back and forth from North to South and from South to North, along the local line of the terrestrial magnetic field until they are eventually absorbed into the atmosphere of the Earth. The internal radiation belt is the area where these particles are stored.

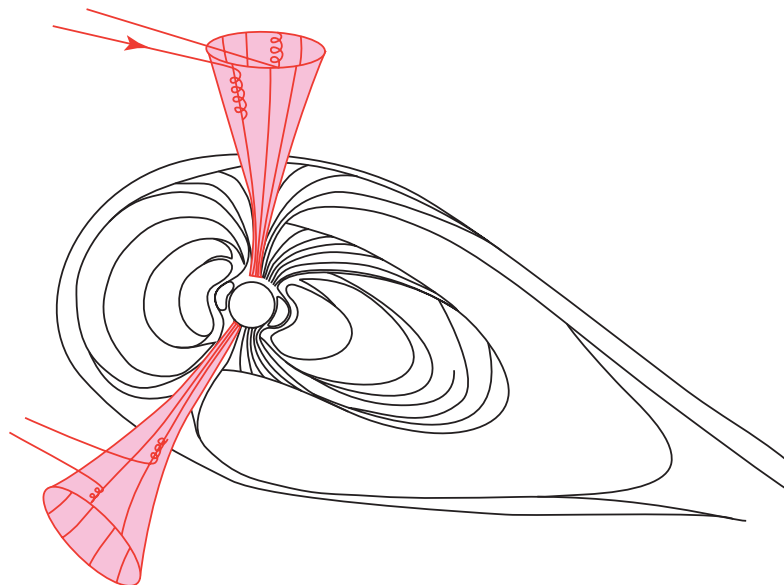


Figure 2.23 - The position of the polar cusps (in pink)

The arrows show the paths of four particles of solar wind trapped along one of the field lines of the cornets. They can then be either directly propelled toward the polar atmosphere or blasted out into space.

One surprising effect of solar activity is its effect on the volume of the internal belt. When the Sun is in an active phase, it emits more energetic particles in greater numbers. The stream that flows along the magnetopause then becomes more dense and more energetic and the likelihood of collision with a cosmic ray from space increases significantly. Fewer cosmic rays pass through this shield and the internal radiation belt becomes thinner. It has therefore been observed that the quantity of cosmic rays in the atmosphere¹⁶ is very closely anti-correlated to the solar cycle: when the Sun is quiet, the amount of cosmic radiation in the terrestrial atmosphere increases. The internal radiation belt varies in function of solar activity but in inverse ratio.

To explain the perturbations of the magnetosphere due to the Sun, there is still one area of our environment that remains to be introduced: the cusps. These are shown in purple in figure 2.23. They are at a very high latitude. In this area the terrestrial magnetic field no longer loops round the Earth, it opens out into space in two big cones, one to the North and the other to the South. The solar particles that pass near their field lines are directly perturbed and can settle into the atmosphere of our planet. Unlike their fellows that went through the plasma sheet, they are not compacted against the magnetosphere nor are they accelerated. Their energy is lower and their effects on the atmosphere also less intense.

This brings to an end the description of the principal magnetospheric regions, those, that is, that play a major part in the relationship between the Sun and the Earth. We can now go on to explain the most spectacular geophysical effect of the interaction between the magnetosphere and the ionosphere: the Aurora Polaris, or Polar Lights.

4.2. THE POLAR LIGHTS

The system of aligned currents (see figure 2.21) can be considered from a purely specific point of view: electrons and ions that rebound off the atmosphere but of which a large part manage to make their way in. These particles are subjected to collisions that create excitation, ionization and heat. In addition, they undergo elastic collisions, like those undergone by billiard balls; these send them shooting all over the high atmosphere, sometimes even propelling them out of it. The lower limit, under which all the particles are absorbed, is about the same as the absorption limit of extreme ultraviolet: approximately 80 kilometers.

16 The quantity of cosmic radiation gradually declines by factor 1,000 between the top of the atmosphere and the surface of the Earth, as discovered in 1936 by the physicist PFOTZER, using detectors on sounding balloons. Atmosphere is in fact an efficacious screen. When it comes under "attack", a cascade of particles is created under the effect of the collisions. They are protons, neutrons and other, more exotic particles, such as mesons. The altitude at which maximum ionization occurs is about 20 kilometers... An atmosphere only slightly more transparent would be unable to protect us so effectively. However, we must remember that cosmic radiation is not very abundant and that only a few important events can reach such low altitudes during one solar cycle.

Excited atoms and molecules are de-energized by chemical reactions or by giving off light. From ground level, we can see magnificent polar lights. From space, satellites can see a luminous oval that is brighter on the night side since the particles are accelerated when they pass through the neutral layer (in what way is still not known) and produce more brutal collisions. In the North, we have the Boreal auroral oval and in the South the Austral auroral oval.

The existence of the auroral oval was confirmed in the 1950s by the first satellites. Photograph 2.27 was taken in the ultraviolet in 1982 by the Dynamics Explorer satellite. At the top of the picture, we can see the Earth lit by the Sun. The radiation is due to the de-energizing of ions and neutrals, excited by UV solar radiation. The night side of the Earth is at the bottom of the picture. The auroral oval can be seen with a significant local increase in intensity (in bright yellow) due to higher-energy particles entering into the atmosphere.

The auroral oval was already well known in the nineteenth century. Geographers had determined its position by careful observation of the occurrence of auroras. There is a permanent one to the South and another to the North of the Earth. Typically, they are situated at a magnetic latitude of between 65° and 75° .

It still had to be explained scientifically. At the beginning of the twentieth century, a young Norwegian physicist by the name of BIRKELAND hit upon the idea of a quite extraordinary simulation. He had a large, glass-fronted box built and inside this he hung a metal sphere, called a Terrella. He then placed an electromagnet inside the sphere. In the corner of the box an electron gun pointed toward the sphere.

He then created a vacuum, insofar as it was possible to do so at that time and by chance that vacuum was roughly equivalent to the atmosphere at an altitude of about 100 kilometers. While shooting electrons toward the sphere, he observed the artificial auroral oval. He had just discovered how polar auroras occur!

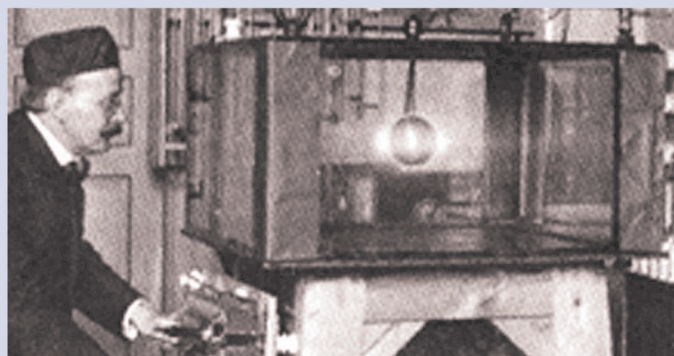


Figure 2.24 – Birkeland in front of his Terrella

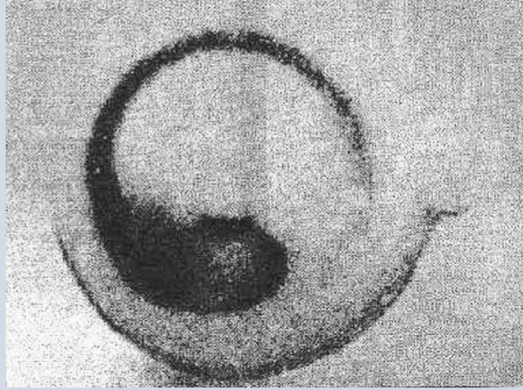


Figure 2.25 - A reconstitution of the auroral oval by BIRKELAND

He described his experiment as an unexpected effect of the electrons recently discovered by J.J. THOMSON (in 1896). Unfortunately he was unable to come up with an answer to questions such as "Where are the positive charges? Where, between the Earth and the Sun, is the conductor through which electrons can travel?". BIRKELAND became a laughing stock, he was misunderstood and was soon a broken man. It was not until well after his death (in Tokyo, in 1912) that the world became aware of the spectacular progress he had provided for the field of geophysics. As a tribute to him, the ion winds that are propagated at the pole have been given his name; they are the Birkeland currents. He had predicted their origin back in 1903.

Below is a photograph of the Terrella as rebuilt by an engineer who is fascinated by the history of science, Terje BRUNDTLAND. In a cellar in Oslo, he found the original, worm-eaten uprights, the glass, the dusty instruments. Using photographs taken at the time, he restored it, rebuilt it, tested it and now the experiment is working again in the auroral observatory in Tromsø, in northern Norway.

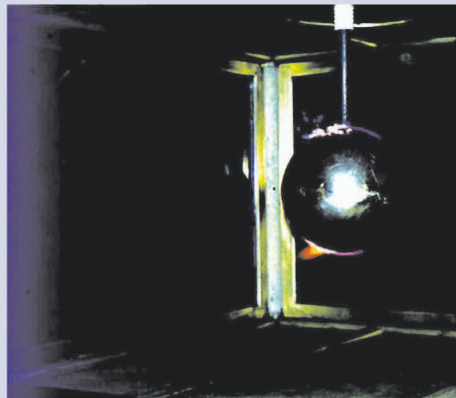
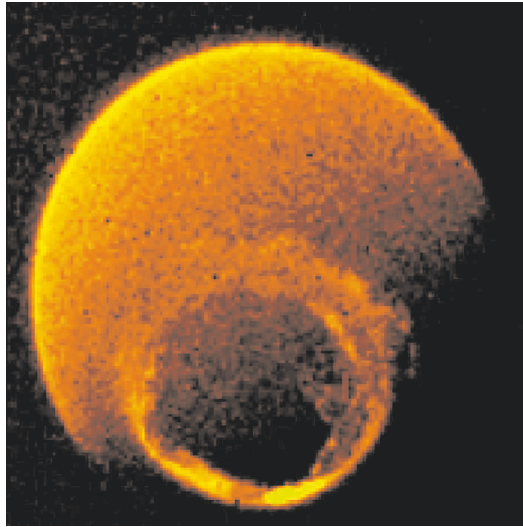


Figure 2.26 - The Terrella work again in Norway!



*Figure 2.27 - The auroral oval stands out on the Earth
(credit NASA/Dynamics Explorer)*

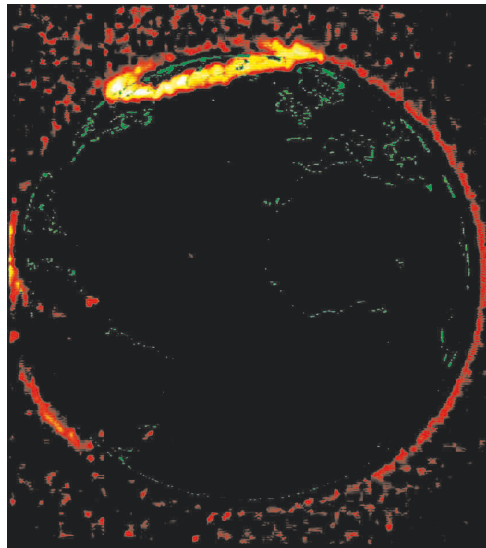


Figure 2.28 - The Earth wearing its crown (credit NASA/Dynamics Explorer)

The existence of the ovals is unrelated to the part of the magnetosphere that rotates with the Earth and that we have called the plasmasphere: it is directly connected with the plasma sheet that is always on the night side of the Earth. Consequently, the ovals do not rotate with the Earth; the Earth rotates below them. They are always present since the solar wind blows continuously.

Photograph 2.28 shows the Earth on February 16th 1982, crowned with a circle of polar lights as Dynamics Explorer crossed the zone in the shadow of the Earth at an altitude of between 3 and 3.17 terrestrial radii. Active polar lights can be observed over the polar regions and cruise over the limb both in the morning and in the evening. The southern oval, which is symmetrical, is not visible in this picture. All around the Earth, we can see the atmospheric emission due to the terrestrial radiation.

From Earth, under the oval, if the sky is clear, we can see polar lights; they are Boreal in the North, Austral in the South.

Typically, the auroral oval is at a high latitude. However, the magnetic axis and the geographical axis are not quite aligned and since the magnetic North Pole is in the North-West territories of Canada, auroras can frequently be observed at geographical latitudes as low as Quebec, at 47 degrees North. It is, however, most unusual to be able to see one from Paris, which is on just about the same parallel but a long way from the magnetic pole.



Figure 2.29 - Aurora Borealis or Northern Lights in Tromsø, in December 1999

The stars that stand out behind the auroral curtains show how weak the luminosity of the auroras are. On the first photograph, the wider spots are Jupiter and Saturn (credit P. Volcke and J. Lilensten Laboratory of Planetology, Grenoble. Technical details: Fujichrome film, 28 mm, aperture 2.8, 400 ASA, filter nil, poses of between 40 and 70 seconds).



**Figure 2.30 - These polar auroras were taken
in the north of France**

During the night of April 6th to 7th 2000, a magnetic storm (see further on) expanded the auroral oval over lower latitudes. The constellation of Cassiopeia can be seen behind the aurora, on the bottom two photographs (credit: G. Dubos, A. Leroy, T. Lambert, M. Besnier and G. Laurent, Uranoscope, Seine et Marne. Technical details: 28 mm, aperture 3.5, 400 ASA, poses of between 1 and 3 minutes).

The colors are due to elements that have been de-energized. It could be said that they constitute the signature that allows thermospheric and ionospheric identification by the analysis of the auroral spectrum: dark blue, purple and greenish- blue for an ion of molecular nitrogen, green and white for a molecule of nitrogen, yellow for molecular oxygen and green and red for atomic oxygen... The visible radiation of the aurora is only part of the overall radiation: some emissions take place in the ultraviolet.

The dynamics of the auroral oval are in themselves a whole section of ionospheric and thermospheric research. Photograph 2.31 provides an insight. Here, the diurnal side of the Earth is top right and the oval is almost entirely visible. The lights of the American towns outline the continent, 80 kilometers below. The wide auroral vortices can be compared to those that occur in a river on encountering an obstacle such as the pier of a bridge or to spirals of smoke. The nature of these instabilities is fundamentally fluid.

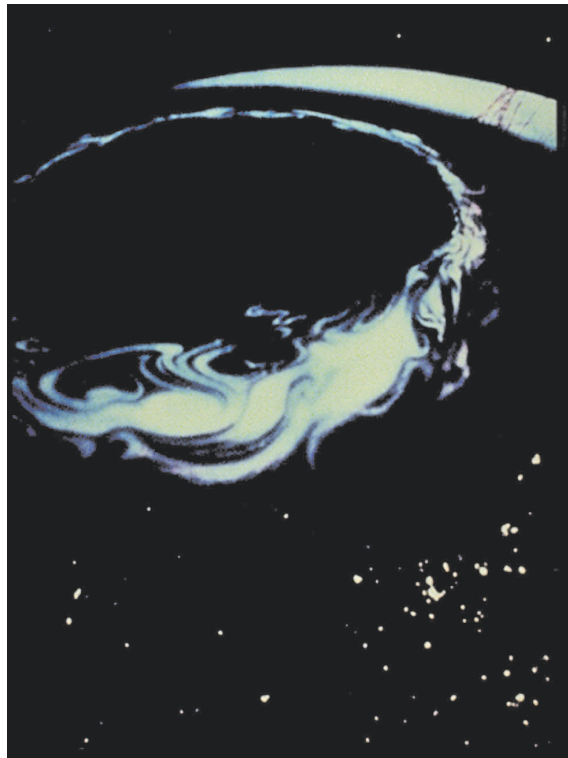


Figure 2.31 - Under the auroral oval with a spectacular dynamic, the lights outline the United States of America (credit DMSP, American Defense Satellite)

Polar auroras have given rise to many beliefs amongst the populations of high latitudes. Not so long ago, on the Lofoten islands, children were forbidden to wave a white cloth, such as a handkerchief, in front of an aurora; since it was feared that the aurora would capture them and carry them up into the sky. On the other side of the Earth, the Australian Kurnais used to hit out at the aurora with a "dead hand", taken from a deceased relative.

The first attempt at a scientific explanation dates back to the Greek philosopher, ANAXIMENES, circa 600 bc. His theory was that the air rising from the Earth condenses to form clouds then, as it rises even higher, becomes scarce and burns up, hence the auroras. This interpretation survived until the seventeenth century, with some slight modifications. At the end of the nineteenth century, knowledge improved a little. In his *Popular Astronomy* (published by Flammarion) Camille FLAMMARION was able to write in 1891: "Terrestrial magnetism has its poles, its meridians, its equator, that move about on and within our globe. Our planet is, in fact, a huge magnet of tremendous strength, estimated by GAUSS to be that of 8,464 quintillion steel bars each weighing one pound and magnetized to saturation point."

Referring to CARRINGTON's observations, he then concludes:

"It is quite probable, almost certain in fact, that this correlation between the state of the Sun and terrestrial magnetism is real and not fortuitous and that there is a magnetic relationship between the Sun and the Earth.

This relationship appears to extend to boreal auroras... The number and the size of the auroras that can be observed each year vary over a period of eleven years, with the peak corresponding with that of the sunspots and flares... It should be remembered that ARAGO used to boast that he could predict an aurora that would be visible in Sweden and Norway simply by observing the magnetic needle in Paris. It is, therefore, hardly surprising that the correlation noticed between the state of the Sun and the compass extends to the auroras."

4.3. MAGNETIC STORMS AND SUB-STORMS

On a planetary scale, there is an event that occurs several times each year giving rise to considerable disturbances: magnetic storms. What are they?

The magnetic field of the Earth is orientated from the South to the North. The solar wind is made up of charged particles in motion, carrying their own magnetic field. When the North-South component of the interplanetary field is in the same direction as the terrestrial field i.e. from South to North, interaction takes place between the solar wind and the geomagnetic field as described previously and forms the magnetosphere (figure 2.15). However, the interplanetary field reverses frequently, influenced by sunspots or coronal mass ejections. Fast solar wind catches up with slow solar wind, compression zones appear (magnetic clouds) and the direction of the magnetic field is perturbed. When solar activity is high, the direction of the interplanetary field can vary very rapidly. When it reverses, from North to South, a sort of neutralization of the geomagnetic field occurs. The particles that near the Earth

can then enter directly into the magnetosphere. Our planet is no longer protected by its field and receives a direct bombardment of protons. The magnetopause can move back toward the Earth by more than one terrestrial radius. It can even move closer than the orbit of geostationary satellites (6.6 terrestrial radii) which are then directly exposed to the bombardment of the solar wind. So long as these effects are confined to high latitudes, we have a *magnetic sub-storm*. However, if the electric fields or the perturbations of the magnetic field make themselves felt at low latitudes, the phenomenon is called a *magnetic storm*. When this occurs, a transversal bar appears in the auroral oval, which takes the form of the greek letter theta. However, these are not the only effects.

The particles that were unable to find a way in on the diurnal side skirt the Earth as described in the paragraph on the creation of the magnetosphere. However, there are some differences: the magnetopause, the shell in which space is governed by the terrestrial magnetic field, is more porous for the particles. They cross it more easily: this is the growth phase of the sub-storm.

Then, owing to the effect of forces of which the origin is not yet fully understood, the energetic particles are propelled toward Earth in characteristic one-minute blasts. This particle precipitation can last for more than an hour. The electric current in the magnetosphere increases in intensity so that the plasmapause (the boundary that separates the part of the magnetosphere that co-rotates with the Earth from the part that is always on the nocturnal side of the Earth) drops to as low as two or three terrestrial radii. The electrons arrive on Earth from the nocturnal side at a high latitude, triggering extremely luminous polar lights and spread northward, eastward and westward in a few tens of minutes. This is known as the expansion phase of the sub-storm, which is an explosive liberation of pent-up energy. The energy released in the high latitude ionosphere can brutally reach 50,000 billion Watts.

Magnetic storms are not frequent and are probably even more complex than sub-storms. They develop over half a day and decay in a few days. During a storm, there is also an increase in ring current. At between 10 and 23 terrestrial radii, the plasma sheet becomes populated, to the extent of 40% of its ion population, with oxygen ions torn away from the atmosphere of the Earth.

Magnetospheric plasma radiates slightly in the ultraviolet, making it possible to take photographs from satellites. Figure 2.33 shows its shape on a large scale during a magnetic storm at about 18.00 hours UT on August 11th 2000. The complex system of currents, accentuated by the storm and combined with the different regimes of co-rotation or convection gives it a very specific structure. We can see an S-shaped tail breaking away toward the Sun. The plasmapause has become very irregular and the energy of the plasma has intensified on the nocturnal side. These manifestations are not well understood and are, therefore difficult to predict.

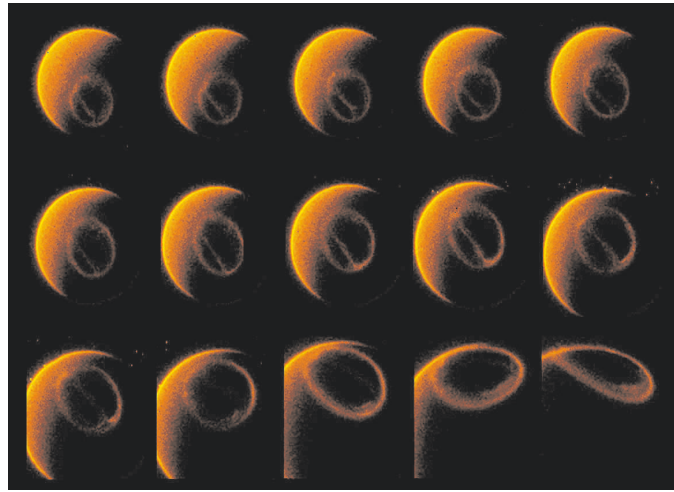


Figure 2.32 - This photograph taken from Dynamics Explorer, shows a sequence of growth and decay of a Theta arc, on November 8th 1981, starting at 14.12 UT and ending at 17.02 UT
The apparent expansion of the Earth is due to the orbit of the satellite as it draws closer (credit NASA).

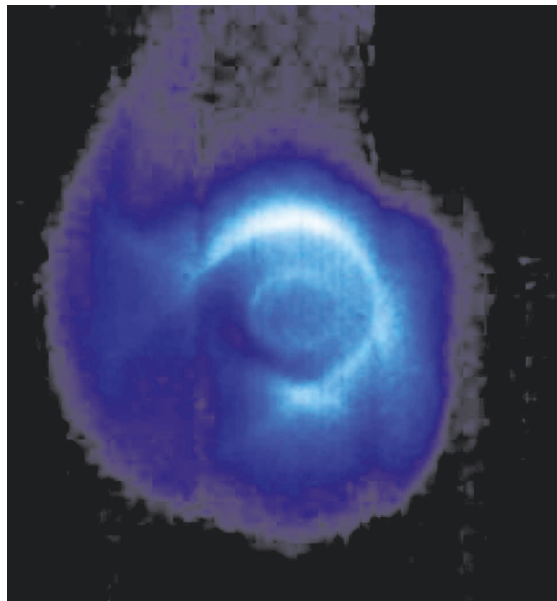


Figure 2.33 - A photograph (in false colors) of the plasma environment of the Earth during a magnetic storm
The satellite is flying over Earth at the North Pole. The intensified radiation of the auroral oval is clearly visible. The whiter sphere represents the position and the size of the Earth. The Sun is in the top right-hand corner of the picture (credit NASA, Scientific Group, IMAGE satellite).

4.4. HIGH ALTITUDE LIGHTNING FLASHES

A final and very recent discovery deserves all our attention as it could lead us to change some of our approaches to the spatial environment. In the previous chapter, we described particle precipitation that is a form of exchange between the magnetosphere and the thermosphere. The polar wind is the release of atmospheric matter toward the magnetosphere. The different layers of our environment are therefore interconnected, exchanging particles or energy. A short time ago a phenomenon that links the lower atmosphere directly to the ionosphere was discovered¹⁷.

These are red or blue flashes that unlike the usual flashes of lightning are directed from the top of the cloud toward the very high atmosphere, up toward the ionosphere. The red flashes are called *sprites* and the blue flashes are called *blue jets*.

Their discovery proved that there are still a great many phenomena about which we know nothing, perhaps right under our eyes and that nature does not willingly accept being scrutinized as we have dared to do in this chapter. Flashes are ionized ducts into which electric energy discharges when there is too great a difference in potential. It was impossible to predict the existence of these sprites or blue jets

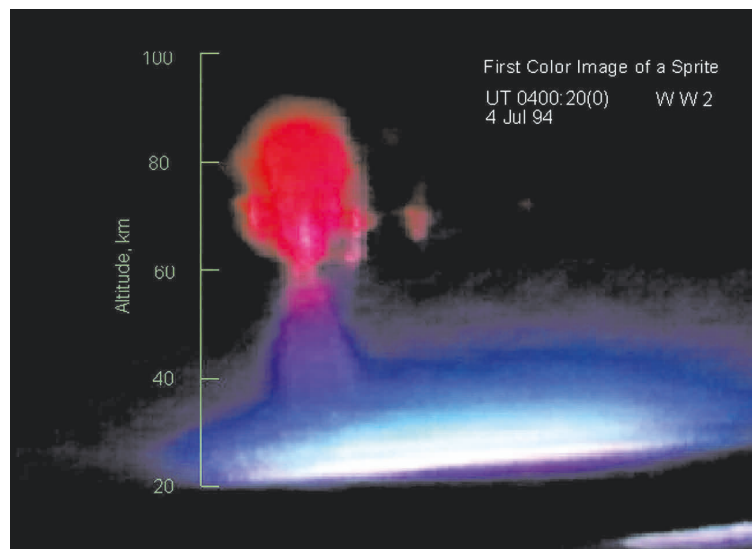


Figure 2.34 - This is the first color photograph of the "sprites", taken on July 4th 1994 (credit University of Alaska, Institute of Geophysics)

17 In 1989, researchers from the Alaska Geographical Institute (R.D. FRANZ, R.J. NEMZEK and J.R. WINCKLER) attempted flying into storm cumuli in small airplanes, partly for their work and partly as a challenge. These clouds are veritable traps for aircraft, with winds that toss them up like wisps of straw and lightning that streaks continuously. However, understanding how they form is essential to atmospheric physics and meteorology and nothing can beat *in situ* observations.



Figure 2.35 - "Sprites" sometimes go off like fireworks!
(credit University of Alaska, Institute of Geophysics)

because the ionosphere at 110 kilometers is so conductive that it is difficult to subject it to huge differences in electric potential. However, these flashes of a new type fill the layers between a few hundred meters and 90 kilometers with ions. These ions are still a little-known source of the ionosphere, be it nocturnal or diurnal and spread out over the whole of the planet. These phenomena may be correlated to other little-known events such as the changing position of the magnetosphere. They could also help provide a convincing explanation as to the existence of a nocturnal ionosphere (where there is no longer a source of ionization from solar radiation) which can be seen even at latitudes that are too low for particle precipitation from the solar wind.

To sum up, the Earth, our planet, is subjected to the heat and light of the Sun, its particle winds and its varying fluxes of electromagnetic radiation¹⁸. Fortunately, the atmosphere and the magnetic shield protect the Earth enabling life to exist. All this existed well before mankind appeared on the Earth and it may well seem that only now are we capable of understanding the effects of the Sun. However, two questions remain:

- ♦ Does human activity modify what we like to call this harmony (which is, of course, relative)?
- ♦ Will technological development based on the use of increasingly low electric currents, micro and nano-technology be possible for much longer in this context perturbed by particles and electromagnetic waves?

The final chapter of *Environment, Societies and Space Weather* should help us form an opinion.

¹⁸ Magnetic indexes have been defined to characterize magnetic phenomena. Appendix 14 describes the present situation.

Chapter 3

TOWARD A SPACE WEATHER



*Figure 3.1 - Sunrise seen from space
(credit J.P. Haigneré, CNES, Perseus mission)*

Various attempts to explain the Aurora Borealis are at the origin of the discoveries concerning the ionized environment of our planet. The first magnetic measurements were taken by VON HUMBOLDT in 1805. It was he who first used the term "magnetic storm" to explain the perturbations of his measurements. Together with GAUSS, he was able to put forward an explanation for the terrestrial magnetic field. The first observation of a solar eruption was in 1859. R. CARRINGTON, a British astronomer, noted a magnetic storm followed about 18 hours later by auroras at a medium latitude. However, at the time it was impossible to say whether this was a coincidence or if there was a correlation.

Thirty years earlier, Hans Christian ØRSTED of Denmark, had noticed that electric wires deflected the needles of magnets. In 1831, the Englishman, Michael FARADAY, proved that inversely a magnet is capable of generating a current. The laws on electromagnetism that followed, standardized by the Scot James Clerk MAXWELL in

1868, were, shortly after, applied to the Sun-Earth relationship by BIRKELAND. In the 1950s, Sydney CHAPMAN was credited with completing BIRKELAND's explanation concerning the connection between eruptions and auroras as well as suggesting a mechanism for the formation of the ionosphere. Some of his theories were questioned and completed by Hannes ALFVEN, a Swede who was awarded the Nobel prize in 1970¹ and who died in 1995.

Geophysics of the space environment really took off in 1958. At that time the cold war was raging and could have degenerated into total war at any time. In this tense climate, scientists of opposing political blocs were hard put to collaborate. OPPENHEIMER, for instance, was accused of collusion with the communists. The first place where scientists from both sides met in strictest secrecy was a village called Pugwash, in Scotland. The ensuing movement took the name of the village and received the Nobel peace prize in 1985. In that context and under the influence of James Van ALLEN and Sydney CHAPMAN, the period between July 1st 1957 and December 31st 1958 was declared the International Geophysical Year.

It is easier to grasp the recent progress made concerning the knowledge unfolded in this book by reading the report drawn up by Paul-Emile VICTOR on the International Geophysical Year:

"Thanks to observations made in the polar regions in particular, the International Geophysical Year brought to light a new theory on magnetic phenomena.

The central core of the Earth, which is highly radioactive, solid and probably made of iron, appears to be surrounded by an "outer" liquid shell, the diameter of which is no more than 7,500 kilometers.

The new theory assumes that the origin of the magnetic field is to be found in the outer shell; at the beginning, the "churned" metal gave rise to a low electric current that generated a low magnetic field. The particles of metal in motion in this field gave rise, in turn, to new currents, resulting in the magnetic field that can be observed at the present time, that influences and perturbs the Moon and, above all, the Sun.

Apparently, not only does our magnetic field capture the particles sent out by the Sun, it also traps emissions from space.

The origin and the mechanics of the renowned polar auroras were also studied in detail, as were those of solar activity that has such an influence on our life on earth.

(P.E. VICTOR, *Man and the Conquest of the Poles*, Plon, 1962)

The Americans and the Soviets engaged in a scientific race of prestige, with both groups transporting tons of equipment and hundreds of people to the poles. Other nations such as France, Germany and Great Britain had no intention of being left

1 Shared that same year with Frenchman Louis NÉEL for his work on the magnetism of solids.

out, so that year of hard labor resulted in a new theory on magnetic phenomena. Physics pointed the way to wisdom; human beings united their knowledge to further their understanding of the environment.

Aeronomy, a branch of geophysics that describes the phenomena covered in the previous chapter, is a relatively new science. The Sun-Earth relationship that it strives to understand has remained identical for several billion years. Our technology, however, has made considerable progress. To transport energy, we now use the same vehicles as the Sun: electromagnetic waves and particles. This energy has numerous fields of application: electricity, communications, positioning systems... This similitude of a physical nature means that there is ever-increasing interactivity between solar activity and our own and, consequently, an ever-growing need to predict solar activity precisely and to measure its impact on society. Imperceptibly, we are moving away from aeronomy and the Sun-Earth relationship toward a new branch of astrophysics, space weather.

1. THE CONSEQUENCES OF SOLAR AGRESSIONS ON OUR TECHNOLOGICAL ENVIRONMENT

1.1. PIPELINES

According to some theories, the magnetic perturbations arising from solar incidents can affect pigeons or cetaceans. However, as far as the corrosion of pipelines is concerned, they are no longer theories: pipelines are made from blends of metals, including iron. Everybody knows that in the presence of humidity iron rusts. This reaction, called oxydoreduction², occurs when electrons break away from the metal.

This corrosion could lead to a major ecological tragedy if oil poured out of a hole in a pipeline in the deserts of Alaska or if fire broke out because of an accidental hole at a point where corrosion had occurred. Pipelines are, therefore closely monitored and protected. To avoid the leakage of iron electrons into the ground, pipelines have a coating of low conduction material and are maintained artificially at a slightly negative potential in relation to the Earth (-0.85 Volts), to prevent the migration of electrons. However, corrosion is increased by the electric currents that spread through the ground during magnetic storms and sub-storms: the difference in potential with the ground can become positive by several volts, resulting in electron leakage. High latitudes are particularly exposed and the pipeline that crosses Alaska from North to South or the network of Scandinavian pipelines are exposed to accelerated corrosion, requiring permanent monitoring in conditions that are often extremely harsh.

2 Oxidation results in electron depletion and reduction in electron gain. In an oxydoreduction reaction, an oxidizing agent fixes one or several electrons provided by the reducing agent.



Figure 3.2 - The Alaska pipeline

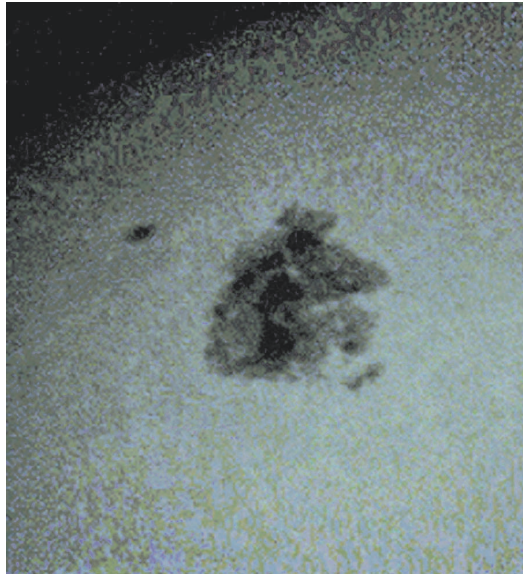
The flow of oil inside keeps its temperature well above that of the ground. Here the ground is a mixture of soil and ice (permafrost). If the ice were to melt and the ground turn into mud, the pipeline would sink down into it. To avoid a catastrophe such as this, the ground has to be cooled. This explains the small towers on either side of the pipeline (credit D. Lummerzheim, Alaska Geophysical Institute).

Repairs to pipelines are expensive, not only because of the hostile environment of high latitudes or deserts but also because to interrupt the flow is a long, delicate operation. If it were possible to measure precisely the currents induced by substorms, maintenance would be more stringent and more economical. In this case, the interest lies in monitoring, rather than predicting, solar activity.

1.2. TRANSMISSION OF ELECTRICITY

The production and distribution of electricity can be severely affected by solar activity. Due to industrial development, the number of electrical networks such as rail, electricity, communication ones has increased and they are interconnected, creating huge antennas that, on the scale of a continent, are excellent inductors for ionospheric currents. During magnetic storms in particular, stray currents spread to the transformers with an intensity that can exceed the regulation capacities, leading to power failure throughout the network.

Although the intensity and direction of these induced currents are extremely variable, their variations in time are relatively slow in regard to alternating current: a few hundred or thousand seconds. Transformers have alternating current –50 Hz in Europe and 60 Hz in North America– and can only transform quasi direct induced currents into heat. In the United States, in 1992, during a magnetic storm, an increase in temperature from 60°C to 175°C was recorded in the transformers. Mention is also often made of the magnetic storm of March 1989, preceded four days earlier by a solar eruption.



***Figure 3.3 - An active region on the Sun,
photographed by the National Oceanic and Atmospheric Administration
(NOAA, USA) at 15.08 hours UT on March 9th 1989***

This area is about 54 times bigger than the Earth. Shortly after this picture was taken, an eruption centering on this cluster of spots developed, sending billions of tons of particles out into space (credit NOAA-SESC).

On March 13th, in 90 seconds, this storm caused a 9,500 megawatts generator and seven electric equalizers to melt suddenly in Quebec and the United States. The load on the rest of the network was such that in a short time it all failed, leaving 6 million consumers without electricity for 9 hours. The same phenomenon led to the overheating and destruction of a transformer in New Jersey in the United States, which cost several million American dollars to replace. Here we do not mean one of those transformers that can be seen by the roadside in small shelters a few meters square but some of the biggest electrical apparatus constructed on earth, each weighing several tons. Having a spare available is not enough, it still has to be transported at considerable cost. Between the failure in New Jersey and replacement, the cost overrun for consumers amounted to \$ 400,000 per day. It is estimated that if a magnetic storm only slightly more violent occurred in the North-West of the United States, the cost would be between 3 and 6 billion dollars, about the same as when a cyclone or an earthquake occurs.

The key parameter when it comes to predicting geophysical induced currents (or GIC in short) is the electric field on the surface of the Earth. This is connected to the ionospheric currents interacting with the magnetosphere that is subjected to solar perturbations. It is therefore essential to predict the whole chain of variations with a time allowance of at least ten minutes. Why is this allowance necessary? Because human operators permanently monitor electricity consumption and adjust production



Figure 3.4 - This transformer in the Delaware River nuclear center plant in New Jersey was damaged by the magnetic storm of March 13th 1989

This is one of the three largest transformers with a total unit of 1,200 MVA. It costs more than 10 million dollars and repairs took more than a year (credit Minnesota Electric Company).

to requirements. Many events have an effect on requirements: for instance, if the average temperature outside drops by 1°, heaters are switched on. This alone leads to a demand on the network corresponding to the production of an extra power plant in a country the size of France or Great Britain. Events like the eclipse of the Sun in 1999, a cloudy passage, the end of a prime time television program all require the intervention of operators.

The cost of overproduction can be counted in millions of euros. The cost of underproduction can be even higher since power lines can break when consumer demand is too high. A false alarm can, therefore be very costly and operators want predictions to be as precise as possible. Generally speaking, detecting the reasons for a genuine alarm and responding in the best possible manner can take a few minutes and these few minutes cost money. For power companies, the aim is simple but will suffer no false alarms: they require sufficiently early warning of where an geophysical induced current is going to occur. When the alarm goes off on the

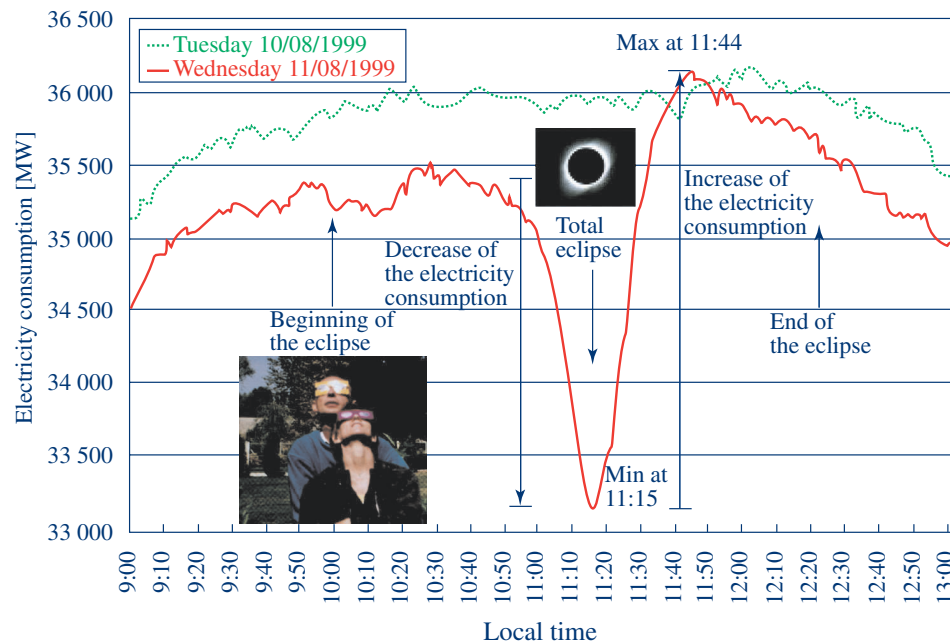


Figure 3.5 - The effect of the total eclipse of the Sun on the demand for electricity in Great Britain, on August 11th 1999

When the eclipse was total, electricity consumption dropped by almost 2,500 megawatts. Immediately afterwards, as people returned home and made numerous telephone calls, it increased to above its nominal value (credit National Grid Company Inc.).

control terminal, the operator immediately knows what type of phenomenon he is up against and can make the right decision: whether to lower the tension of the network; include in the production circuit one or two extra power plants that are not concerned by the induced current; purchase current from adjacent countries...

1.3. RAILWAYS

Geophysical currents can, perturb signaling systems, although fortunately this is not a frequent occurrence. This was almost certainly the case in Sweden in 1982. The fact that this very rarely happens does not mean that we can drop our guard, for a rail crash endangers the lives of a great many people. Cosmic radiation also probably has an influence on railways. Losses of power were noticed on the German high-speed train ICE as soon as it was put into service in 1990. These incidents did not occur at regular intervals but it was noticed that they never happened while the train was going through a tunnel. A detailed study showed that electronic components were affected by cosmic rays, the effects of which were amplified by the intense electric fields of the monitoring apparatus.

1.4. TELECOMMUNICATIONS

Sometimes during a trans-Atlantic phone call your party complains that you can hardly be heard yet his voice comes over to you pretty loud. He keeps asking you to speak up while you are shouting yourself hoarse asking him to please stop shouting! This again is due to ground induced currents that act like an amplifier in one direction and a resistance in the other on the currents traveling along the submerged cables that cross the ocean.

Let us now leave the ground of our planet and examine how and where the waves we use for our communications are propagated. Long-waves (30-300 kHz) and medium-waves (300-3,000 kHz) used for navigation or radio, skirt the Earth in the low ionosphere. Short or high-frequency waves (3-30 MHz), used by radio hams, mobile phones, FM radio or taxis are reflected on the ionosphere. UHF or VHF waves (lower than 3 GHz) used for telephone, television or FM radio cross through the ionosphere in all conditions but undergo attenuation and changes of phase that depend on the structure of the electron column they have to cross.

Any change in the structure of the ionosphere, therefore, has an effect on the propagation of these waves. Since the ionosphere is very sensitive to radiation and to the precipitation of charged particles, it can be perturbed for a few hours following magnetospheric storms and show considerable structural irregularities that lead to phenomena of interference and, possibly, absorption. A volume of atmosphere warmed up by a perturbation in the auroral region can move about in a veritable bubble of plasma, whilst retaining its characteristic high temperature and concentration. These bubbles, that can measure between a few times ten and a few hundred kilometers, are obviously quite a nuisance for all latitudes telecommunications and are very hard to forecast. For example, from the 22nd to the 23rd of May 2003, all telecommunications (TVs, radios, and phone) were shut down in Tromsø (Norway) for several hours. It was the probable effects of quite a small flare that occurred on the sun 2 days earlier. It hit the Earth and created very strong local disturbances.

Global positioning systems³ can also be perturbed. The first facet of these systems is a constellation of satellites that orbit at altitudes of around 20,000 kilometers, distributed in such a way that any given point of the globe is always visible from at least four of them. One important feature of a global positioning system is reception at ground level. The satellites are equipped with atomic clocks that have been gauged to correspond. These cesium clocks are at present the most precise

3 The system created in the United States is the GPS. It consists of 24 satellites on 6 different orbits, at an altitude of 20,200 kilometers; the operations control center is in Colorado. Another system, GLONASS, created by Russia, consists of 24 satellites on 4 orbits, at an altitude of 19,000 kilometers. The first system has been operational since 1994 and the second since 1996. That of the European Community, which should be put into service during the first decade of the twenty-first century, is called Galileo. However, Europe already has receiving stations for the American and Russian systems.

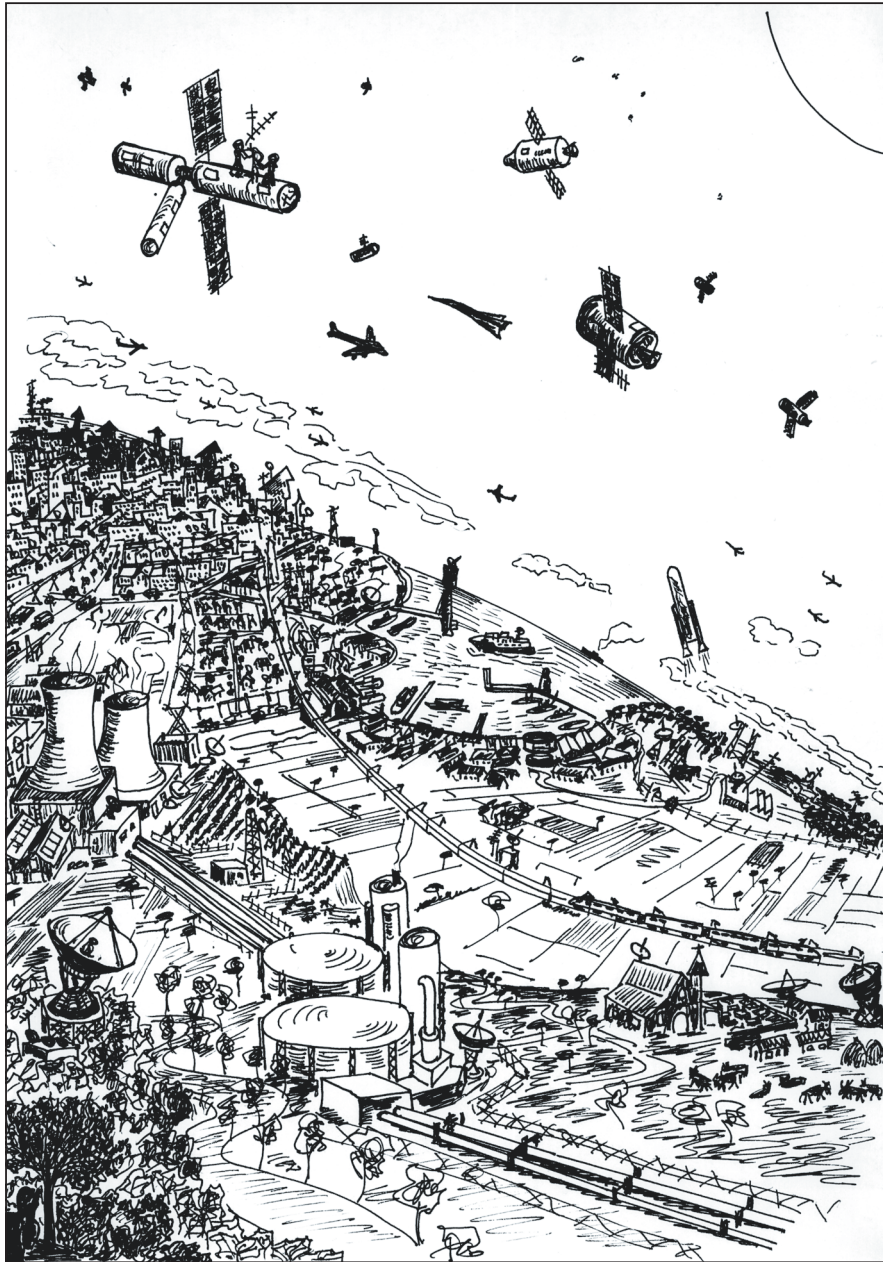


Figure 3.6 - *I'd had more than enough! I really needed a few hours' break up in the woods, away from all the noise and pollution. The week had been pretty hectic, after that business of the pipeline leakage the week before, those astronauts who didn't have time to protect themselves because the early warning satellites malfunctioned and that same old solar eruption melting our transformers –power is still cut off on the north side of town... Oh, I nearly forgot to warn Geneviève for when school comes out! ... Oh no! The cellphone's not working! That's another satellite gone on the blink! (C.J. mountain of Pelemont, March 2007)*

instruments available for measuring time, with a margin of error of one second over a million years, on satellites built to last for about seven or eight years. The price to pay for this precision is their weight: global positioning satellites weigh more than 800 kilograms.

Each satellite continuously emits two types of data: its position and the precise time of emission. A ground station receives this data from several emitters and can calculate the distance between its position and each of the satellites. Using this data, the station can calculate its own position to within a few meters. The accuracy of the data concerning the position of the satellites themselves is crucial. To check this, stations installed all over the planet at specific points transmit the positions emitted by the satellites to a monitoring center. The center uses forecasts concerning solar activity, the state of the magnetosphere and the state of the ionosphere through which the data-carrying waves have to pass, predicts in turn the position of the satellites for the next twelve hours and transmits the data. The data is updated continuously.

Users of global positioning are on the increase: military missiles, aviation, other satellites, emergency vehicles, a growing number of automobiles, ships... The frequencies used are in the range of a gigaHz. A strong magnetic perturbation, that results in variations in electron concentration in the atmosphere, can lead to errors of between several times ten meters and 1 kilometer when determining positions. These errors can have dramatic consequences in some cases for airplanes or ships.



***Figure 3.7 - On the island of Svalbard, this globe protects
a NASA satellite monitoring antenna
(credit C. Lathuillère, Laboratory of Planetology, Grenoble)***

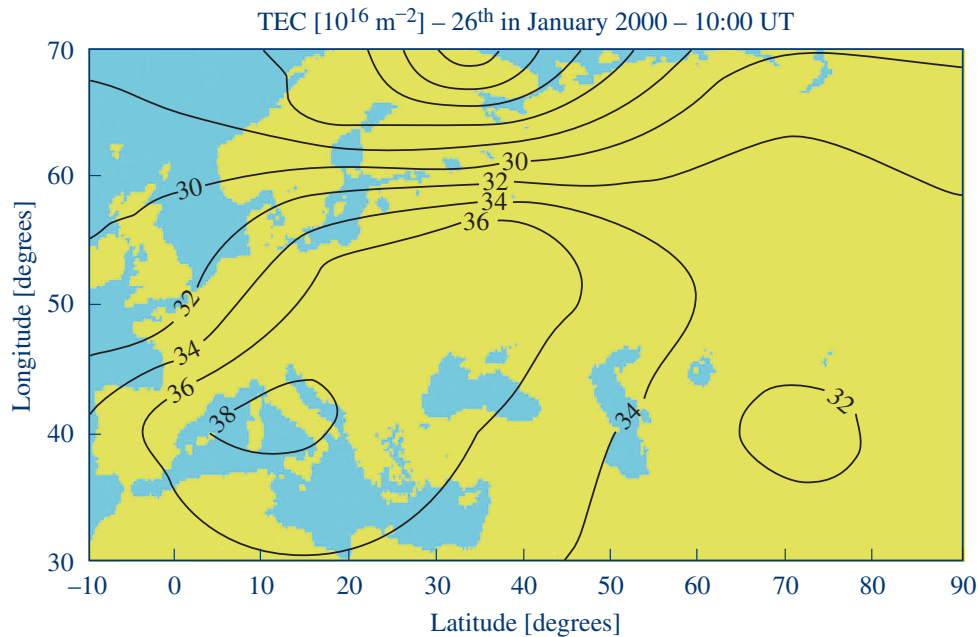


Figure 3.8 - A map of total electron content over Europe on January 26th 2000
 It has been made more legible by dividing each number by 10 million billions (10^{16}).
 38 on the map means that above this line, in a column 1 square meter in section
 and from ground level up to 20,000 kilometers, there are 38×10^{16} electrons in the
 ionosphere (credit Royal Appleton Laboratory, Great Britain).

To avoid them, positioning systems can function with two frequencies instead of just the one: the differences between the two independent computations allow extremely accurate correction. However, this is a very expensive solution since it increases the weight of the equipment taken on board satellites. It is, therefore, necessary to use models to know precisely the electron content of the atmosphere in real time. Charts are published several times a day and operators, in particular those working with space, use them as a basis.

1.5. SPACECRAFT LAUNCHES

Let us consider the risks of incident during take-off of a spacecraft. Owing to cost, it is the launching of a rocket that has been most closely analyzed.

What happens when an Ariane 5 rocket is launched? The operations take place in Kourou, Guiana. Twenty-two days are needed to carry out inspections and adjustments. The first 13 days are spent assembling the different stages of the rocket in which power, equipment and propellant are stocked. Then the rocket is checked out for electricity and leaks and is prepared for transfer into the final assembly building. In here, during the third week, what is known as the "payload", consisting



Figure 3.9 - The European Space Operational Center (ESOC) of the European Space Agency (ESA) in Darmstadt, Germany

of the satellites that are to be put into orbit, is installed. Then, after a final inspection, fuelling and pressurization begin. This is a very dangerous phase: at the slightest spark it can all go up in flames. On the 22nd day, the rocket is towed to its launching zone. Countdown then begins, 6 hours before scheduled take-off, at hour H0. The final and most dangerous fluids, ergols, are added at H0 minus 4 and a half hours. Mechanical loading of the launching ramp is carried out at H0 minus 1 hour. Six and a half minutes before H0 the "synchronized sequence" begins. At H0 launching



Figure 3.10 - Ariane 5 being launched from the Kourou base (credit Arianespace)

begins with the ignition of the engine of the Principal Stage⁴. If all goes well it is the turn of the two Powder Acceleration Stages to be ignited, enabling the launcher to lift off. These stages are very soon cast off, at an altitude of only 60 kilometers, and fall down into the sea. The principal stage is cast off so as to drop into the Pacific Ocean, 1,200 kilometers off the coast. The satellite(s) are then put into orbit. All this lasts only 40 minutes.

The risks must be reduced at all stages of launching: one to two days beforehand, when the rocket is set up on the launching pad; when fuelling begins and, finally, when the automatic synchronized sequence is triggered. The risks of breakdown linked to the spatial environment are a failure in telecommunications and damage to electronic components of the rocket through intense radiation. According to calculations carried out by the CNES launch control, the probability of failure of Ariane 5 due to this source is 1% during a very violent solar eruption. In the absence of solar eruptions, the probability is one per thousand.

1.6. SATELLITE FLIGHT

Satellite orbits are ellipses⁵ characterized by the point at which they are closest to the Earth⁶ –the perigee– or that at which they are farthest away –the apogee. Another important parameter is the inclination, i.e. the angle formed by the orbit and the equator: an inclination of 0 degrees corresponds to a satellite in equatorial orbit, whilst 90° is a purely polar orbit⁷. Depending on flight altitude, it is also called Low Earth Orbit (LEO, at about 1,000 kilometers) Medium Earth Orbit (MEO, approximately 10,000 kilometers) or high orbit: in this case it is a geostationary orbit (GEO), where equatorial satellites rotate with the same angular speed as the Earth, so that they always fly over the same point, at a fixed distance above ground level of about 36,000 kilometers.

Many other types of orbit can be imagined, from those that always fly over the same two local times (one during the night and one during the day) to those that are synchronized on the Sun ("helio-synchronized") and see the Earth rotating below the satellite.

The electronics of satellites play an important part in orbit control and satellite positioning: should it face the Earth? At any specific angle? Should it be directed toward the Sun? Toward a star? This is attitude control.

4 Often shortened in PS, PAS...

5 The law of surfaces, used when processing the orbits of planets (see appendix 12) also applies to those of artificial satellites.

6 For bodies other than the Earth, the terms periastron and apastron are used.

7 Appendix 21 gives details concerning the orbital parameters of satellites.

The risks of deterioration of satellites increase with the time spent in space. Satellites with an inclination of less than 51.6° and an apogee of between one and eight terrestrial radii cross one or two radiation belts at each rotation. These belts have high concentrations of energetic particles and expose the satellites to their bombardment. If the inclination of the satellites is more than 80° , they also have to pass through the polar cusps, where they undergo the direct influence of the solar wind.

The damage they sustain was very soon taken into consideration. It was noted that when they fly through magnetospheric plasma, differences in potential appear on board, triggering electric discharges that damage instruments. In other cases, highly energized particles accumulate in certain parts of the satellite, having the same effect. Endeavors have been made to solve this problem by using less conductive materials, particularly for the thermal tiles outside the spacecraft. The cables and the micro-electronics taken on board in particular are confronted with the same problems: their very miniaturization makes them extremely sensitive to the slightest electric discharge.

Electrons penetrate the shroud of the satellite; ionize in cascade all that they come into contact with and create X-rays. A binary memory or processor component can switch from one state to the other under the influence of a heavy ion from the Sun, or secondary ionization on board (in other words, ions and electrons created by the collision of light solar ions or radiation). "Switching" in this case means changing zero into one or vice versa. This may seem unimportant, but if we consider that this 1 could be the 1 of 10,000,000,000, the difference can be huge. Here we have what specialists call the *Single Event Unit* (SEU) effect that can also be created by very energetic and consequently very ionizing cosmic radiation. This can lead to failure of a dielectric component.

Described as "the first satellite for ecology", the European Space Agency's ERS-1 (European Remote Sensing) was launched by Ariane in March 1991. At 1 billion dollars, 2.4 tons and a diameter of nearly twelve meters, it carried on board an array of instruments designed to observe climatic anomalies, ocean levels, the dynamics of marine currents, over the whole surface of the Earth. ERS-1 was placed on a quasi-polar, helio-synchronized circular orbit, at a mean altitude of 780 kilometers. Its mean local solar time of passage above the equator in the north-south direction was 10.30 hours. Along with radar, altimeters, laser and radiometer it carried apparatus built to measure speed and distance, so as to determine the exact position of the satellite and its orbit to permit geodesic localization of the ground stations: the PRARE instrument. The latter was the victim of a SEU occurrence that led to failure, making determination of the position of the satellite and, therefore, of the measurements taken, far more difficult⁸.

8 ERS-1 stopped functioning on March 10th 2000, after failure of its attitude control. ERS-2, launched on April 21st 1995, took over from ERS-1.



Figure 3.11 - ERS-1 as seen by SPOT-4

ERS-1 is an observation satellite. To the right of the picture we can see the platform and the solar panel and, on the left, the 10 meter×1 meter long rectangular antenna of the synthesis aperture radar and two shorter, narrower antennae (3.6 meters×0.25 meters) inclined at 45°, used to measure the wind field. The very shiny zones on the picture are due to the reflection of the Sun on the highly reflective coatings that protect the satellite. ERS-1 travels on an orbit that passes 41 kilometers under that of the SPOT satellite. This proximity enables SPOT-4 to see details of 50 centimeters on ERS-1. However, since it flies lower, ERS-1 is faster and overtakes SPOT-4 at a relative speed of about 250 kilometers per hour (credit CNES).

It is unanimously agreed that these SEU occurrences are going to be the major concern of satellite constructors in the years to come. In spite of their name, these events can follow each other in quick succession! Up to twenty were observed in one day following a solar eruption in October 1989, on a NASA relay satellite (TDRS-1) and its attitude control was badly damaged. Extremely costly ground procedures had to be used to keep it on orbit. In situations such as these, commercial portable computers are extremely sensitive to interference ionization. On the MIR space station, they sometimes had accidental cut-outs every hour!

In some circumstances, it is possible to take preventive measures against one particle. However, their effects can accumulate: in the CMOS technology used for on-board electronics in particular, differences in potential appear after several repeated attacks. They lead to gain reduction in the transistors, a reduction in the effectiveness of the solar panels, interference in the diode lights or the photo-

detectors or downgrading of instrument resolution, as observed on the TOPEX⁹ satellite launched on August 10th 1992.

The position of the satellite has a noticeable difference on the effects. For instance, in the magnetospheric tail, the satellites are immersed in an energetic plasma. Their surface is electrically charged and, once again, a difference in potential occurs inside the craft, damaging sensitive instruments. The magnetic storm of March 1991, for instance, shortened the life of the geophysical satellite GOES¹⁰ by three years.

During the storm in March 1991, a new radiation belt appeared for several days, increasing by factor 400 the micro-failures on board satellites. Too high a surface charge can be fatal, as was the case on January 20th and 21st 1994 for ANIK-E1, a Canadian telecommunications satellite.

Several studies concerning on-board charging of satellites have been carried out, for instance for FREIA¹¹ that was launched on October 6th 1992 and finished its operations four years later. It had an inclination of 63°, and passed through aural zones with each orbit, with a perigee of 601 kilometers and an apogee of 1,756 kilometers. The sole purpose of all the experiments was to study the Earth and its relationship with the Sun; 73 kilograms of science were on board! During the first two years of its



Figure 3.12 - An artist's impression of the TOPEX-POSEIDON satellite
(credit CNES-NASA)

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- 9 The Topex-Poseidon mission, which was the most important collaboration between the CNES and NASA, is intended to further understanding of the part played by oceans in climatic variations. The satellite takes precise and repetitive measurements of sea levels, marine currents and their effects on global climatic changes. Altimetrical measurements enable scientists to study tides, waves, geophysics and marine winds.
- 10 This, or rather these, satellites are the basis for the meteorological observation and forecasting system in the United States of America.
- 11 FREIA, the Swedish geophysical satellite, is named after the Norse goddess of fertility. Far from being sweet and gentle, however, this empress of the kingdom of the Norse gods, alongside Odin, is a warrior, with the power of life and death, love and combat, fertility and black magic! After a battle, half the dead are hers by rights, for her own enjoyment.

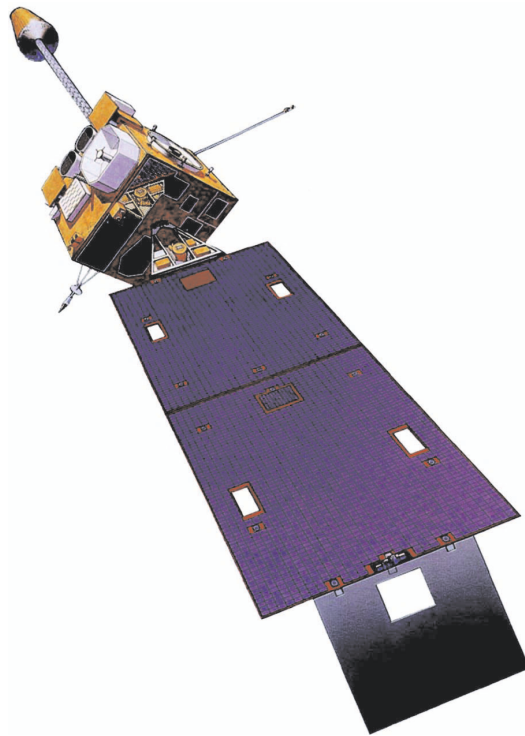


Figure 3.13 - An artist's impression of the GOES satellite (credit NASA-NOAA)

activity, during a phase of decreasing, rather low solar activity, approximately ten cases of untimely charges were registered and studied. None of them were fatal to the instruments but they affected them for periods ranging from a few seconds to a few hundred seconds, with differences in potential of up to 2,000 Volts. What makes it difficult to foresee these events is that they occur on both the night side and the day side of the Earth.

However, FREIA is not a representative craft: it was purpose-built for ionospheric research and was extremely well protected. The tendency nowadays in space is to use commercial electronic components that are less costly than specially-made circuits. And lower cost often means greater fragility...

Attitude controls are key parts of on-board equipment since they inform the satellite of its position in space. Deterioration following a magnetic storm can lead to the loss of a satellite, as was the case during the solar eruption of July 14th 2000 mentioned in the previous chapter. This eruption and a coronal mass ejection that occurred at the same time gave rise the following day to a magnetic storm that altered the orientation of the Japanese satellite ASCA, whose mission was to observe the universe in the X-ray range. The batteries supplied by solar panels discharged, and that was the end of the satellite.

The most exposed field is undoubtedly that of constellations of telecommunication satellites. These are tens of light-weight micro-satellites that cover the whole of the Earth with a network which makes it possible to telephone from any point to any other. The Skybridge¹² constellation is a good example. It is made up of 80 satellites in low orbit and is designed to supply private persons as well as companies with a transmission band with performances similar to those of future broad-band terrestrial technologies. This platform provides fast access to the Internet and to various interactive services such as telecommuting, distance learning, video-conferences and interactive games. The huge number of applications for constellations such as these make protection against failure due to discharges of solar origin absolutely essential.

The need for industrial cost-effectiveness and the enormous cost of sending these satellites into orbit would normally dictate the use of standard instead of custom-built components. However, the risk of failure is increased due to the large number of satellites. In particular, a very strong magnetic storm could affect the whole fleet. The annual cost of anomalies during flight due to spatial environment is already estimated to be about thirty million dollars for the United States alone.

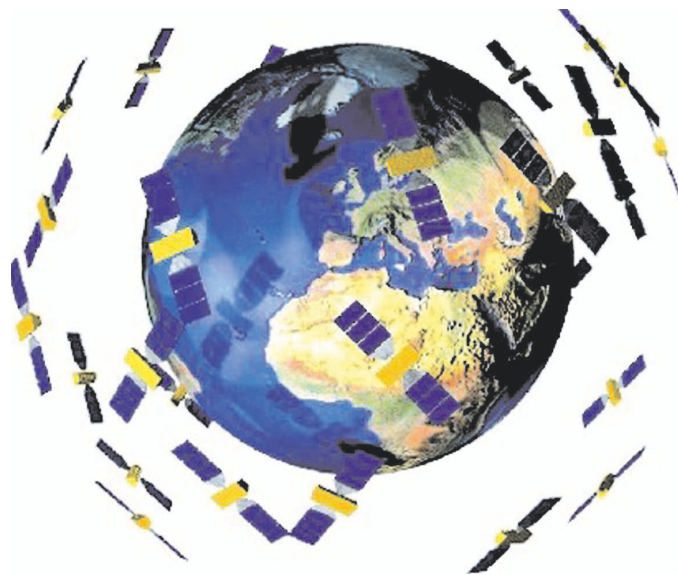


Figure 3.14 - A representation of the Skybridge constellation (ALCATEL space)

12 The SkyBridge program is piloted by Alcatel Alstom, in partnership with Loral Space and Communications (USA), Toshiba Corporation, Mitsubishi Electric Corporation and Sharp Corporation (Japan), SPAR Aerospace Limited (Canada), Aérospatiale (France), the CNES (France), COM DEV Int. Ltd. (Canada) and the Société Régionale d'Investissement de Wallonie (Belgium).

The problems of on-board damage are not the only ones encountered. When the Sun is in an active phase, an increased number of protons heat the atmosphere which then expands¹³ and carries the satellites upwards, like a boat on a wave, the unfortunate result being that ground controllers temporarily lose track of the orbits!

In the atmosphere, our spacecraft are also exposed to various frictions that are difficult to estimate and that have the opposite effect: the satellites come closer to the Earth. According to the laws of mechanics, when satellites near the Earth they do so by increasing their speed of rotation. Normally the half-big axis of the orbit of a satellite decreases by about 1 meter per day; corrected by means of small auxiliary engines. Variations in atmospheric concentration, most violent when solar activity is agitated, lead to a drop in speed that can be as much as several tens of meters per day. The position of the satellite is then known with poor precision: to within less than 8 kilometers. Between November 2nd and November 11th 1993, high electric fields due to solar perturbation triggered winds of a few hundred kilometers per hour at altitudes of 300 kilometers and latitudes as low as that of France. Satellites typically travel at 8 kilometers per second, and are normally not greatly affected by atmospheric winds but in conditions such as these friction is no longer negligible.

In October 1997, the half-big axis of SPOT-2¹⁴ varied by more than 30 meters per day for three days. A few meters of uncertainty can be hundreds too many. This is, of

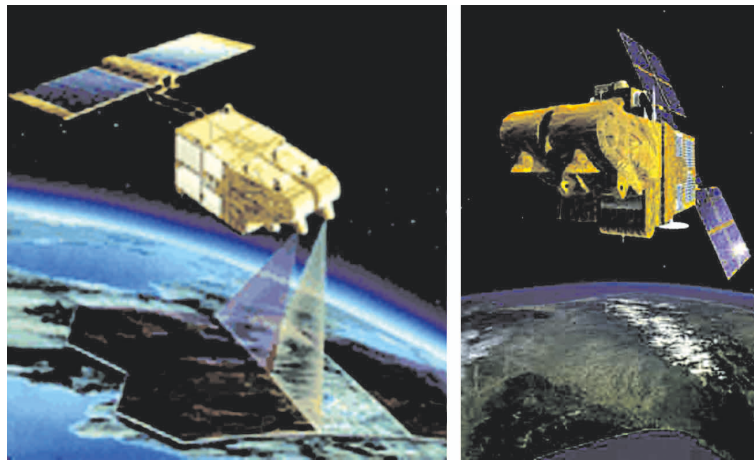


Figure 3.15 - Two artist's impressions of the SPOT satellite (credit CNES)

13 Expansion "pushes" the dense layers of the lower thermosphere upward. At 400 kilometers, the number of neutral particles per unit of volume can be multiplied by ten.

14 SPOT ("Satellite Pour l'Observation de la Terre" or in english: satellite for the observation of the Earth) is a high resolution spatial optical imaging system. This program, decided on by the French government back in 1977, was thought up by the CNES and carried out in collaboration with Belgium and Sweden. It consists of a series of satellites and ground support infrastructures designed to monitor, program, receive and produce images.

course, the case with ERS-1 and 2 that fly on a quasi-circular orbit at an altitude of nearly 780 meters: in order to know the level of the sea, it is essential to know from where it is being measured. A precision of 5 centimeters is required concerning their height, even though their orbit can vary by 10 meters per day when solar activity is intense.

1.7. THE REENTRY OF SPACECRAFT INTO THE ATMOSPHERE

It is also necessary to have precise data concerning friction when a spacecraft reenters the atmosphere. This is the case with space shuttles, International Space Station modules or, in the case of an accident, with any craft that falls back to the ground. At the end of the 1970s, Skylab –82 tons– was the first American space station. Launched by a Saturn-V rocket, the same as the one used for the Apollo missions to the Moon, it soon ran into technical problems due to vibration during take-off and also to the detachment of an anti-meteorite shield that tore off one of the solar panels. A piece of the torn-off panel hit the second panel, preventing deployment. Twenty-eight days later, repairs were carried out by a first crew of



Figure 3.16 - The Skylab station photographed by a second crew (CONRAD, KERWIN and WEITZ) as they left for Earth (credit NASA)

astronauts. On July 11th 1979, 84 days and one hour after it was launched, it crashed into the Indian ocean. No-one was able to foresee the precise location of its fall more than a few hours before it happened.

In 1980, 4 months beforehand, the orbit-computing programs were unable to forecast with greater precision than to within 10 days, when the MAGSAT satellite was going to reenter the atmosphere. As you can imagine, they were not able to say where!

Not all aspects of friction are negative: many low-orbit satellites use it to assist flight. However, it is not easy to evaluate because the composition of the atmosphere is not well known. An error of a few hundred meters and the satellite is lost. Since aerodynamic forces are dominant at the flight altitudes of low orbit satellites, below 600 kilometers, the objective at the present time is to be able to predict the future position of a satellite to within 20 kilometers 24 hours beforehand, including during perturbed periods.

1.8. SPACE DEBRIS AND ITS EFFECTS

Space debris can have the same devastating effects as radiation, particles or atmospheric warm-up. Some of it is of natural origin: interstellar dust, meteors, meteorites from the ablation of comets. However, an increasing amount comes from rocket stages, retired satellites and fragments of various spacecraft.

It is common practice, when a satellite reaches the end of its life, to let it fall purely and simply into the atmosphere, where it is supposed to burn out. This fall often takes place over a long period, since it is not boosted by an engine: the launcher stage of a geostationary satellite takes between 10 and 10,000 years to fall back down, depending on whether its perigee is at 200 or 600 kilometers.

Nowadays, out of all the objects inventoried in space, only 6% are functional satellites, 22% are retired satellites, 17% top stages of rockets and the remaining 55% are miscellaneous fragments and debris¹⁵. We are leaving a crucial problem for future generations to solve.

As it breaks up in the atmosphere, a spacecraft triggers debris that can become dangerous projectiles for other satellites or, what is worse, for a manned space station: a particle of 100 grams transfers more than 3 megajoules on impact! In 1990, the American satellite LDEF was recovered by the space shuttle after 6 years in flight. When it was examined, more than 30,000 impacts of debris could be seen with the naked eye, perforations of 3 millimeters in the aluminum walls and deterioration of its coating of Mylar and Teflon that had pilled under the effect of solar radiation. Another well-known example is the French satellite CERISE, the

15 Most of the figures concerning space debris are from the CNES. This space agency takes the problem very seriously, making great efforts to identify and keep track of the debris that are already there and to reduce the number in future.

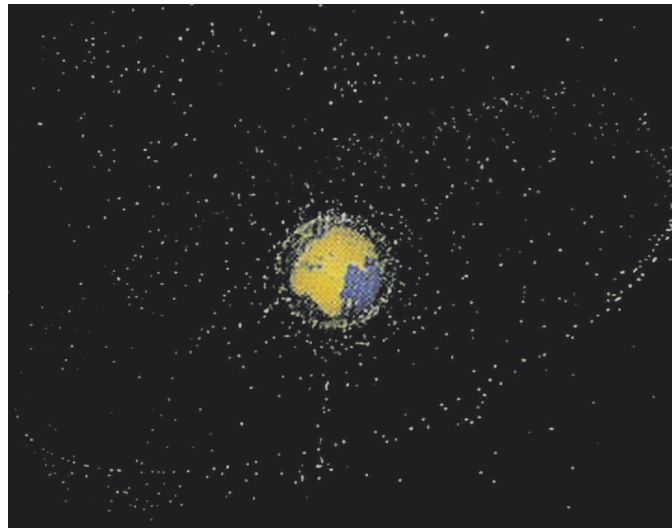


Figure 3.17 - Each point of this picture represents a space debris (in 1993)
The ring of debris of satellites in geostationary orbit, 36,000 kilometers from the Earth, can be seen quite clearly (credit ESOC).

stabilizing arm of which was sectioned in July 1996 when it collided with a debris from the explosion of a stage of an Ariane rocket. This rocket had sent the satellite SPOT-1 into orbit in February 1986. The stage exploded 9 months later, scattering more than 700 fragments bigger than a fist. Since then, Arianespace have opted for "passivation" of the stages after the satellites are in orbit. This essentially means emptying the tanks completely to avoid explosions. Furthermore, space agencies have agreed that retired geostationary satellites be shifted about 200 kilometers above their orbit so as to draw them slowly away from the attraction of the Earth. However, no solution has been found as yet to make low orbit satellites harmless.

So a close watch must be kept on this debris. This is possible for fragments that are bigger than 10 centimeters across and of which there are (only) about 8,500. "Only" is in regard to the 110,000 fragments which vary in size from 1 to 10 centimeters, and which are about 300 times less numerous than the smallest scraps that are impossible to localize. Altogether, more than 2 million kilograms of debris are in orbit above our heads. The risk of losing a satellite through a collision with one of these fragments is, at the moment, 10,000 to 1, but increases exponentially with time. It is already quite an undertaking to keep track of the largest pieces: atmospheric tides can displace them over hundreds of meters in a few minutes. For example, during a violent solar event, the monitoring center (NORAD) lost track of 1,300 of them!

It is therefore necessary to quantify in real time any modification of the thermosphere over the whole of the globe, so that spatial operators can keep track of debris. Forecasts on a scale of a few hours are also necessary to have time to prepare avoidance procedures for satellites or the International Space Station. This was the

case in July 1997 for the SPOT satellite, due to a risk of collision with debris from the Thor Agena launcher. This avoidance led to two days' loss of filming and a fuel consumption of 400 grams. That doesn't seem much? Wrong! That's enough fuel to keep it on orbit for three and a half years!

When they fall Earthward, the largest objects with a mass of more than 5 tons, are only partially destroyed. It is still not possible to predict the precise point of impact since the atmosphere of the high layers is still not well known. Other potentially dangerous satellized objects are those equipped with electro-nuclear generators. One of these –COSMOS-954– reentered the atmosphere for the first time in 1978, triggering fears of planetary radioactive contamination if its shield had proved to be insufficient. Fortunately, the catastrophe did not take place: the pollution could have been very dangerous had it occurred in the lower atmospheric layers and we still know nothing about the dangers of this type of object exploding at a very high altitude. For the time being, all that space agencies can do is monitor and forecast falls, the aim being to improve their models and acquire a know-how that will, in future, enable them to control falls. Apart from COSMOS-954, reentry of two Soviet satellites with an electro-nuclear generator, an orbital station (SALIOUT-7) a Chinese military satellite (CHINA-40) was monitored and analyzed from January 1978 to March 1996. SALIOUT-7 was a spectacular reentry. This station, with a mass of 40 tons, was launched in 1982 on a low circular orbit of 350 kilometers and neared the end of its life at the beginning of the 1990s. When the Russian satellite control center decided to bring it back, the CNES went into alert, to the extent of putting all available means of observation into play 24 hours per day in February 1991. The



Figure 3.18 - Only a wide angle could photograph a station as big as MIR!
(credit Russian Space Agency)

experience acquired was primordial when it came to modelizing the re-entry of the Russian station MIR, which had a mass of 140 tons¹⁶. The fall of what used to be called the "space datcha" was induced and controlled by a "Progress" vessel docked to the station. As it reentered the atmosphere it broke up into 110 tons of debris, the remaining 30 tons falling into the Pacific ocean. Most of the debris were burnt up at altitudes of less than 90 kilometers.

2. OTHER IMPACTS OF SOLAR ACTIVITY

Up to now, we have dealt with fairly technical aspects of solar activity, through very physical, well identified phenomena, for which solutions can be found, even though some concern mankind directly. Other problems arise in fields relating to environment and human activity. What are they?

2.1. BIOLOGICAL EFFECTS

Radiation from space, in particular from the Sun, has considerable biological effects. Laboratory experiments on spores, bacteria, plant seeds and animal embryos have shown that impacts of heavy ions lead to microlesions. Rats suffered permanent damage to the retina. What is worrying is that these lesions are far more serious when the tissues have first been irradiated with X-rays, i.e. in a medium that can be compared to that of the thermosphere. Side effects were worse and cells took longer to heal. Naturally, experimentation as such has never been carried out on human beings. All the data available has been obtained from manned flights, victims of atom bombs and occupational illnesses of workers in contact with radioactive material. Consequences of irradiation by rays or particles can be classified in different categories. Short-term effects appear between a few minutes and 2 months after exposure to radiation: burns, vomiting, headaches... Long-term effects appear several months or several years later. They range from system disorders that reduce the life-span –usually cancers– to genetic modifications.

Doctors have tried to define a unit of radiation, the sievert¹⁷ and, for each age of a human being, a threshold below which there is no known risk. In nature, each of us is exposed to an average of 2.4 millisieverts per year. An X-ray exposes us to a dose of 0.7 millisieverts. A dose of 2 sieverts is lethal. The symptoms described above appear at about 200 millisieverts. It is considered that there is a 1% risk of stomach cancer when exposed to 1 sievert.

16 To avoid a tragedy that could have resulted in hundreds of thousands of victims had it fallen on a large city, the fall of the MIR station was provoked.

17 The sievert is the dose equivalent. Its equation to dimensions is $L^2 T^{-2}$. A dose of 1 sievert corresponds to radiation of 1 Joule per kilogram of matter irradiated.

The thresholds put forward for the NASA astronauts are 1 millisievert per day, 250 millisieverts per month, 500 per year and 1,500 over the whole of their career. A solar eruption exposes astronauts to a dose of several hundred millisieverts, especially during extra-vehicular activity. Certain solar events have given off 1 sievert per day at one AU¹⁸. On August 4th 1972, the dose received at moon level was equal to 7 sieverts per hour when at a maximum. By an incredible stroke of luck, this bombardment took place in between missions Apollo 16 and 17. Had the astronauts been unfortunate enough to be exposed to it, in spite of the shroud of their module, they would have received an integrated dose of 15 sieverts, and this would most probably have been fatal.

However, there is no cause for undue alarm: no serious accident that can be attributed to radiation has been deplored so far, whether by Americans or Soviets. In spite of these risks, a great number of countries have started to assemble the International Space Station.



Figure 3.19 - The first version of the International Space Station

Once finished, it will have a mass of about 400 tons and a living area of 1,300 cubic meters, as much as two large jumbo-jets. It will be 108 meters long and will accommodate a crew of three astronauts during the assembly phase and six to seven when it becomes operational from 2003. There will be six laboratories, including the European Columbus laboratory (to be seen on the left). The ESA is also working with NASA on an emergency vehicle and will be a part of the project via the automatic transfer vehicle (credit NASA/ESA).

18 This radiation is absorbed by the terrestrial atmosphere and is not a threat to life on the surface of the planet. However, it exposes astronauts to serious accidents.

Astronauts are taking off at an increasingly sustained rhythm to go up and assemble it. How can these space mechanics be protected? For a start, they need a sarcophagus cabin with protective shrouding. To be effective, if it is made of aluminum it must have a voluminal mass of 50 grams per cubic centimeter. This makes it very heavy and therefore very costly to send into orbit. Next, eruptions have to be forecast. By the time they become visible, it is too late: the astronauts have already been exposed and there is no point in going back into the station. Forecasting must, therefore, be based on the time required for the astronauts to transfer from space to their cabin: a few minutes.

Unfortunately, all the problems cannot be solved simply by defining "tolerance" thresholds. Recent studies have shown that just one very energetic proton can cause considerable damage, amplified by the radiative environment (X-rays, ultraviolet rays...) along its path, even if it remains well below the threshold. At the present time, we need to understand these devastating effects so as to define how astronauts can best be protected.

However, astronauts are not the only people who fly. Although the flight crew of passenger aircraft are protected by the atmosphere and the cabins they spend a great



*Figure 3.20 - Extra-vehicular activity during the Perseus mission
(credit J.P. Haighneré, CNES)*

many hours in the air. Measurement of the amount of radiation received is complicated by the fact that every air hostess, steward or pilot knows that if they exceed a dose of 100 millisieverts over 5 consecutive years or 50 over one year, they will be grounded. A large airline found this to their cost: personnel were throwing away or "forgetting" the badges supposed to measure the radiation received. Campaigns were therefore launched to measure radiation on the planes themselves, on Concord or Boeing. Nothing alarming was found: 307 microsieverts¹⁹ on a return flight from Tokyo to Paris, 56 for Paris, Los Angeles or Buenos Aires... However, for high altitude flights, especially military flights, emergency procedures are put in place to divert flight plans according to solar emission conditions.

2.2. *THE CLIMATE*

Geophysical and historical records bear witness to the fact that mankind has already experienced several changes, over relatively long time scales as far as the climate is concerned and over a few years as regards meteorology. Several phenomena play a part here. Some have a terrestrial geophysical origin, such as the continental drift, ocean currents, vulcanism. Others are of "extraterrestrial" origin, like the position of the Earth in space, the fall of bodies into the atmosphere... A priori, these fields are not related to solar activity, even though it is obvious that sooner or later we shall have to standardize the knowledge we have acquired if we wish to understand our planet.

The influence of fluctuations of the solar source can also be of the utmost importance for the terrestrial climate. This influence can be direct: a variation in the total irradiation leads to a direct response from the temperature on the Earth. Solar radiation varies according to the nature of the emission site: a spot does not radiate in the same way as a facula or a coronal hole, so climate is directly correlated to solar activity. A variation of 0.3% of the solar constant (i.e. 4 Watts per square meter) results in an average variation of 0.4°C of the average temperature on the Earth. It is, therefore, hardly surprising that certain studies show an influence of the 11-year solar cycle on some meteorological phenomena. It has even been possible to establish such a correlation over the last five centuries, using the existing records of sunspots²⁰. There is also some spectacular evidence of the influence of solar activity on the terrestrial climate. For instance, the little ice age from 1550 to 1750 when winters were so cold that the principal rivers of mid latitude Europe froze

¹⁹ 1 micro = 1 thousandth of a milli.

²⁰ It would seem that after 1980, the correlation is less true. This could be explained by the greenhouse effect due to human activity. However, it would be dangerous to draw conclusions simply on the basis of this correlation since, using the same results published in 1995 by two Danish meteorologists, K. LASSEN and E. FRIIS-CHRISTENSEN, some analysts are trying to prove that there is no global warming while others, on the contrary, see it as proof that warming exists.

over. Between 1650 and 1750, there was a heavy drought in the South-West of North America. This whole period corresponds to the Maunder minimum (1645 to 1715) during which there were no sunspots.

There are more subtle combinations. The impact of cosmic rays, (still to be confirmed), is one of them. This cosmic radiation is that of other stars in the universe or of the active nuclei of galaxies. Due to their remoteness, only the most energetic particles reach the Earth; the others are halted by collisions during their long journey. These energetic particles are, primarily, protons and electrons of several megaelectronvolts. When the Sun is active, the magnetopause thickens since there more solar wind particles skirt the magnetosphere. They form a more effective screen against cosmic radiation. During a calm period, on the other hand, cosmic rays pass more easily through our magnetospheric cover. It seems that cosmic radiation favors the formation of nucleation cores in the lower atmosphere, on which droplets of water can condense, giving rise to clouds. The physico-chemical process is still not well understood, but measurements taken during the last solar cycle showed that on a planetary scale nebulosity is higher during a period of low solar activity than during a period of high activity, probably owing to this process.

Naturally, we have only mentioned combinations for which we have experimental backing. We have no idea whether all the changes in the thermosphere and the ionosphere due to fluctuations in the solar ultraviolet have an impact on the climate. Only a short time ago, this question in itself would have seemed inappropriate, since we had got into the bad habit of partitioning our research. The Sun, the solar wind, the magnetosphere, the thermosphere, the mesosphere, the stratosphere, the troposphere... the theory according to which each layer interacts with the others is recent and is just beginning to take shape. It was only in 1988 that researchers²¹ showed that an increase in the concentration of some gases leads to a drop in the temperature of the intermediate atmosphere. Assuming that the concentration of carbon dioxide and methane is multiplied by two at 60 kilometers, they proved that the temperature of the mesosphere would drop by about 5 Kelvins, while above 200 kilometers, it would drop by 40 Kelvins. What could lead to an increase in the concentration of these gases? The answer is: pollution in the troposphere. It is thought that these concentrations really will have doubled by the middle of the twenty-first century.

The consequences of this drop in temperature have not yet really been assessed. One of them will be the contraction and, consequently, lowering of layer F which will drop down by about 15 to 20 kilometers. This has been christened the "falling sky" theory. A fall such as this, of approximately 200 to 300 meters per year, is still difficult to measure. It can obviously not be regular, since it depends on solar activity.

21 The Belgian G. BRASSEUR and the American HITCHMAN.

To date, no research has been implemented on the impact of this falling sky above our heads, whether in terms of radiation filtering or particles. A whole field of geophysics remains to be pioneered²².

2.3. *INSURANCE COMPANIES*

Between 1989 and 1998, one of the biggest insurance companies²³ (one of those that insure their colleagues of a lesser caliber), insured the launching and operational life of various satellites for more than 5.6 billion dollars (16 billion dollars, all companies included). Reimbursements amounted to about 4.6 billion dollars, which still left a good profit. However, in 1998, for the first time, reimbursements exceeded the premiums. During the same period, up to April 1st 1998, 51 satellite missions failed, 37 during launching phases or sending into orbit. Here is a fictitious disaster scenario.

A solar event of a rare violence triggers a particularly strong magnetic storm. Intensity is slightly higher than the previously-mentioned eruption of August 4th 1972, which would have killed astronauts on their way to the Moon, or the proton event of February 23rd 1956 that expelled 45 times more cosmic solar rays than the usual level. The solar wind pushes the magnetopause downstream from the geostationary satellites which then find themselves directly in the line of fire of the solar particles. A certain number of attitude controls break down: these satellites are lost.

Transmission instruments stop functioning. At a lower altitude, a few hours earlier, tens of satellites had already been lost as thermospheric expansion caused them to be lifted upward by the atmosphere. The largest debris are scattered and one of them perforates a wall of the International Space Station, endangering the lives of humans on board. On the ground, electric power plants in Scandinavia and Canada stop working because several generators melt. The loss of telecommunications creates indescribable chaos; several people take advantage of this state of affairs by using data network that are still valid to carry out lucrative stock market operations, while their competitors are unable to communicate.

The cost of such a catastrophe is such that insurance companies go bankrupt and cannot reimburse the satellites they were supposed to cover. Large banks, that are

22 A final problem, that could have an influence on the climate, is worth mentioning. The diameter of the Sun is not known precisely, yet it is a vital parameter if we want to know the solar constant. Do we even know whether or not it varies ? Between 1650 and 1760, J. PICARD, P. LA HIRE and T. MAYER tried to observe it using the capacities of the instruments available at the time. In spite of error ranges of more than 2,000 kilometers, they brought to light a reduction of the solar disk. If we complete this with more recent and reliable measurements, this decrease amounts to approximately 350 kilometers per century, to which we may have to add global pulsation that is not very well known with a cycle of 3, 120 and 400 years. There are a few interpretations of these variations but they are still working hypotheses.

23 Cecar and Jutheau.

their stockholders, also go bankrupt. It only takes a few days for the Sun to bring about the "crash" of western economies.

Unless...

- ♦ Unless, on the one hand, it can be proved that this is a natural catastrophe, which would suit the insurance brokers fine, for obvious reasons. This is why they are part and parcel of the non-scientific developers involved in research into the relationship between the Sun and the Earth.
- ♦ Unless, on the other hand, a scientific and technological department is capable of giving the alarm a few days or a few minutes beforehand. This would enable satellites to be put into standby mode and, if possible, rotated so as to present a protected side toward the solar wind.
- ♦ Unless, finally, scientists have managed to produce the necessary protection for the worst of these solar occurrences, in the same way that dams are built to withstand the maximum flood levels predicted by hydrologists.

2.4. MILITARY DEFENCE

Certain military requirements are identical with those of civilians: controlling energy distribution, ensuring the continuity of telecommunications, protecting satellites. Others are specific. For instance, in some countries, long-range detection is still carried out by HF radar known as *trans-horizon*. During a magnetic storm, although they are still capable of detecting the presence of a target, they lose their precision and are unable to find its whereabouts. In the case of an airplane, the operator generally has a few minutes to localize it. However, if the object detected is a missile, this time drops to a few seconds.

The armed services are not only eager for knowledge of the environment, they would also like to have an influence on it. They have seen that atmospheric atomic explosions pumped up radiation belts. In 1962, this led to the loss of a satellite. Now, the question they are asking themselves is "how could we perturb these belts during a conflict?". The enemy, taken by surprise, would lose track of all their spacecraft in intermediate and low orbit and, therefore, just about all their telecommunications and this, as recent conflicts have shown, ineluctably leads to defeat. The satellites belonging to the winning side would also be subjected to modifications of the environment but with these being guided, their orbits could be kept under control.

There are other means of action to hostile ends: VLF waves can induce particle precipitation in the thermosphere which, if harnessed, could be used to trigger targeted satellite bombardment. Powerful transmitters can modify the ionosphere and, therefore, the propagation of telecommunications with a view, once again, to making the opposing systems inoperative. A military saying states "If you know the ground and you know the weather, victory will be total". Weather now includes space: the United States created the 55th Squadron of Space Weather, used by the US Air Force during the "desert storm" operation in Iraq.

2.5. TOURISM AND EDUCATION OF THE PUBLIC

Polar auroras are one of the spectacular and magnificent sights that can be seen. Travel agencies offer packages to Lapland nowadays but there is no guarantee that the traveler will be able to watch an aurora: it has to be nighttime (which is not the case in summer) there must be no clouds and some solar activity one to two days before the planned observation. An operational forecasting service would make it possible to assess all the opportunities for observation. Knowing that there is a good chance of seeing an aurora at a given date, tourist guides could adapt the trip accordingly.

Furthering the knowledge of polar lights not only has the advantage of giving intense enjoyment to the observers, it also helps to make the public aware of the strong connections between the Earth and the Sun. One of the paradoxes of the study of the Sun-Earth relationship is that it reveals often potential dangers to users who ignore them. The reasoning of a great many industrialists can be summed up by: "Everything has worked just fine up to now so why should things change in the future?". Convincing them to take precautions against dangers they have not yet experienced, often at great cost, is an exercise in communication for which scientists are generally not trained. Auroras may help. The next solar maximum is expected in 2011: it is impossible to say how advanced our societies will be by then but it is highly probable that owing to technological progress they will be even more sensitive to solar activity than they are at present.

3. SPACE WEATHER IN ORDER TO FORECAST

3.1. ITS BIRTH CERTIFICATE

On January 6th 1997, at approximately 16.00 hours UT, the LASCO instrument on board the SOHO satellite observed a coronal mass ejection about two solar radii from the photosphere. The first estimations seemed to indicate that it was an important phenomenon and, above all, that it was coming straight toward the Earth. Estimations were made difficult by the fact that it was seen from the front, not far from the solar equatorial plane. However, it appeared to be traveling at roughly 450 kilometers per second. At this speed, the solar wind was expected to reach SOHO about January 10th. Unfortunately, the EIT telescope was stopped for telemaintenance. However, the X-ray telescope on YOHKOH was able to film the eruption.

The fact that this eruption had not been foreseen suffices to show the point we have reached in this new science. Only the previous day, pictures of the Sun showed little activity. It was true that a tiny bright point and a few sunspots could be seen to the west of the solar center but there was nothing to warn observers.

By chance, most Sun physicists were gathered together for a work session between January 7th and 9th. Amidst general enthusiasm, colleagues from other branches of geophysics were contacted and asked to put their instruments on alert.

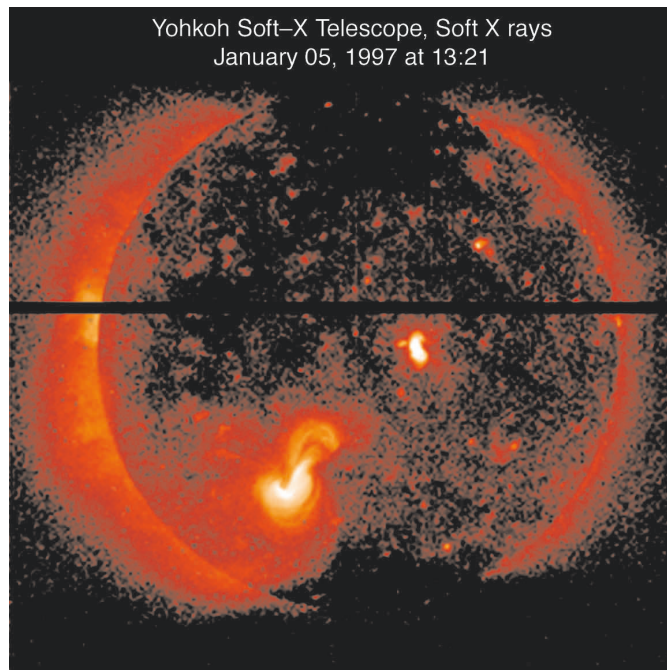
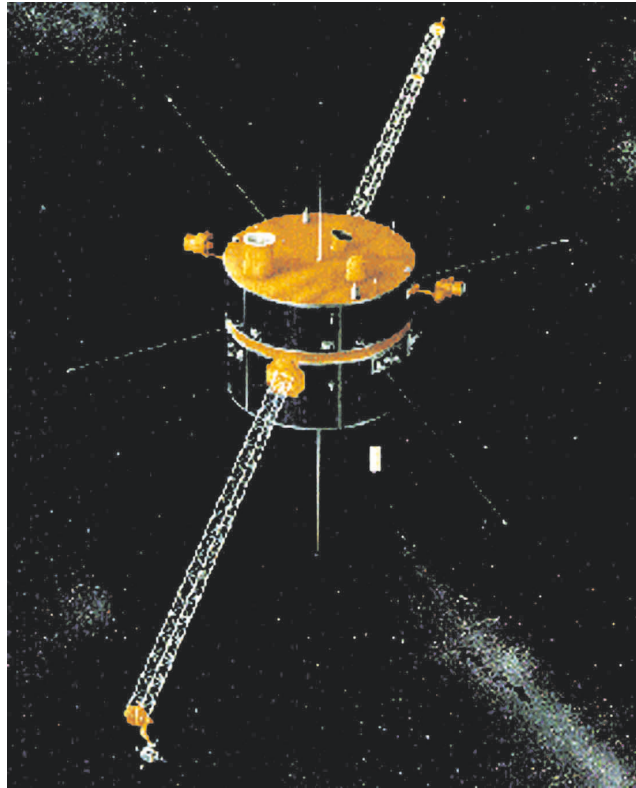


Figure 3.21 - The eruption flares up on the Sun like a big S-shaped streamer (credit YOHKOH; ISAS/LPARL; NASA)

Obviously, data from the proton detector on board SOHO (the CELIAS) were much-awaited on January 10th. Just before midnight UT, the detector measured a sudden increase in solar wind velocity, from 350 to 430 kilometers per second; particle concentration just about doubled, increasing from seven to thirteen particles per cubic centimeter. The importance of the phenomenon was confirmed; four hours later, velocity increased again, up to 520 kilometers per second –that is, almost 2 million kilometers per hour– while concentration now dropped drastically to only two particles per cubic centimeter.

The WIND²⁴ satellite was at less than a hundred terrestrial radii in front of the Earth, with all its instruments in monitoring mode. Less than one hour after SOHO, WIND, in turn, detected a shock wave, signaling the arrival of the magnetic cloud. This arrived at approximately 04.45 hours UT. At that precise moment, the vertical component of the magnetic field, which up to then had been orientated northward, span round to the south with increased intensity. It took about 12 hours to return to its state of equilibrium.

24 Launched on November 1st 1994, WIND is the first satellite of the ISTEP project; it flies between the Earth and the Sun to measure solar wind.



*Figure 3.22 - The mission of the WIND satellite is to monitor solar wind
(credit NASA)*

By chance, GEOTAIL²⁵ was on the dayside of the Earth. It is usually confined within the magnetosphere but following this eruption it crossed the boundary, i.e. the magnetopause, several times. Now the solar wind blew in gusts that pushed it earthward; now it calmed down and released it.

However, not all the satellites above our heads are for scientific observation. TELSTAR-401 is responsible for transmitting the signals of important clients such as the American television channels ABC, Fox or PBS. It belongs to the AT&T telecommunications company, one of the biggest in the world. Nobody knows precisely what failed due to the magnetic storm (at 00.15 hours UT) on January 11th. However, all the ground stations suddenly lost contact with it and were unable to find it again, in spite of all the best efforts of the operators.

25 GEOTAIL is a satellite belonging to the Japanese Institute of Space and Aeronautic Science (ISAS) and NASA. Launched on July 14th 1992, it is used to study the dynamics of the terrestrial magnetosphere from approximately 8 up to 200 terrestrial radii.

This was quite a blow for AT&T, since they had just signed a contract with Loral Space & Communications Ltd., under the terms of which the latter was to purchase its satellite subsidiary, Skynet. The transaction was worth 712.5 million dollars and included the unfortunate TELSTAR-401, which had cost a mere 200 million dollars to build, launch and insure!

At ground level, solar auroras increased in number. The mission of the POLAR satellite, launched on February 24th 1996 as part of the ISTP, was to study the Poles and polar cusps. It was able to capture the auroral oval in real time.

The sub-storm began on January 11th, toward 10.30 hours UT, when the auroras first started to intensify. They were particularly perceptible on the Earth in places where the local time was 23.00 hours or 03.00 hours in the morning. A quarter of an hour later, the auroral oval spread at one and the same time toward the Pole and the east of the Earth, i.e. toward sunset. Then a second intensification occurred where it was 21.00 hours local time on the ground, with very bright auroral drapes. After another quarter of an hour, extremely brilliant auroral lights started to sparkle over the whole oval with extraordinarily luminescent periods.

The loss of a communications satellite under the watchful eyes of researchers was a revelation for the public. In the United States alone, about ten television programs covered this on such well-known channels as CNN or CBS. It made headline news in more than thirty daily papers throughout the world.

This event, which is rare but not exceptional, told the world just how vulnerable we are to the Sun's anger and to what extent the weather of tomorrow will be that of space.

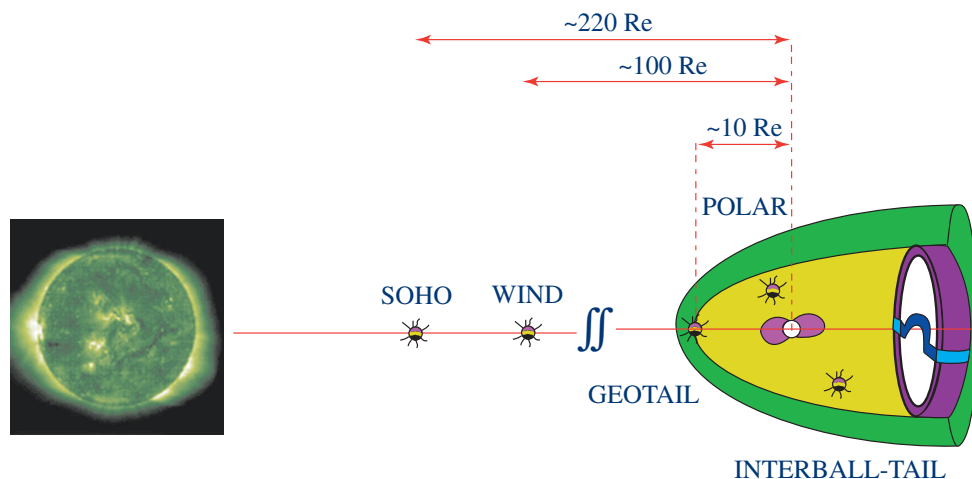


Figure 3.23 - The configuration of satellites in the Sun-Earth system on January 6th 1997 (credit ISTP)

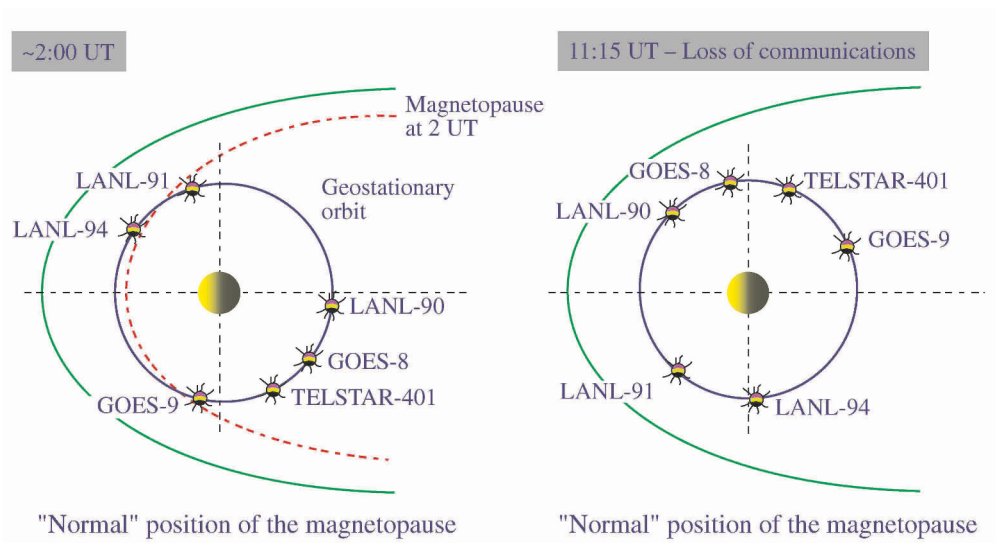


Figure 3.24 - The position of geostationary satellites (on the blue circle)
 The normal position of the magnetopause is shown in green. Its supposed position is shown on the left-hand figure, in red, at 02.00 hours UT. To the right, we can see the position of the TELSTAR satellite when it was lost.

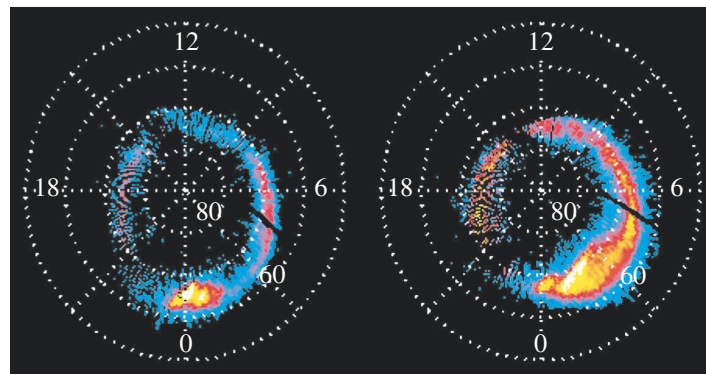


Figure 3.25 - The POLAR satellite passes over the North pole and photographs the auroral oval at 03.37 hours UT, to the left, then approximately 50 minutes later, during the next orbit
 The pictures were taken in the ultraviolet. The local times are shown on this representation (12 means midday, just opposite the Sun). An outstanding expansion of the oval can be seen toward 1 in the morning (local) (credit POLAR/NASA).

3.2. A SCIENCE THAT IS STILL IN ITS EARLY STAGES AND ITS APPLICATIONS

Space weather will have to forecast and quantify particle emission and solar radiation, the geophysical reaction of the magnetosphere and the atmosphere and its possible incidence on human technological environment. From the point of view of

the scientific world, it is not merely an offshoot of aeronomy but a new branch of astrophysics, with countless repercussions²⁶.

In the long run, the services offered by classic weather forecasting will have their counterparts for space: television and radio forecasts, Internet sites, answerphones... Scientists are a long way off and must brace themselves for the same sarcastic remarks as those usually aimed at their colleagues who deal with classic meteorology: "See, they were wrong again, they only forecast an electric field of 5 millivolts per meter and it's 15! Those space weathermen never get it right!".

We shall need to acquire knowledge of unequalled accuracy concerning the Sun and the magnetic environment of the Earth. This means finding a way to predict solar events that arise on the hidden side of the Sun and are liable to menace our planet as the Sun rotates. We need to find unmistakable signs of this activity: one or more for the photon flux, others for particles, still more of interaction with terrestrial magnetism, without forgetting auroral activity, the ring current and radiation belts. Some, such as sunspots for instance, that have been recorded since about 1,700, we already know well. Since 1947, measurement of the solar flux at the wavelength of 10.7 centimeters reflects more or less accurately the global activity of the star. Magnetic field variations at high or low latitudes have been known and analyzed since 1868. However, these global parameters do not provide sharply quantitative knowledge of phenomena with sufficient precision.

For instance, we are partly capable of *describing* the solar magnetic field but quite incapable of *predicting* it, with its various irregularities and, in particular, the triggering of coronal mass ejections. The same can be said of the photon flux and of life on the Earth, in particular in the ultraviolet and X-rays. In the interplanetary medium, we cannot quantify the dynamic pressure of the solar wind or the frozen interplanetary magnetic field found there. Consequently, it is as yet impossible to determine in advance the position of the magnetic shield formed by the magnetopause: is it on this side or the other of the orbit of geostationary satellites?

The characteristics of the radiation belts are not yet well known either. Furthermore, they also depend on the cosmic radiation of all the other stars, that also have to be kept under surveillance.

The phenomena which enable solar particles to enter the magnetosphere are still not understood: the aperture on the day side when the solar magnetic field reverses is only a model, a theory which stands up better than others to the facts. Our knowledge concerning the porosity of the magnetospheric wall or of the collisions in the reconnection zone on the night side is relatively poor, for lack of observations.

26 However, this does not stop some people from trying! For instance, it would cost 500 million euros. To replace an astronaut costs 100 million euros. It is estimated that operational space weather would save worldwide space development a few hundreds of millions of dollars. Raw figures such as these, that may seem cynical, are indispensable to political and industrial decision-makers before the launch of a program of space weather.



Figure 3.26 - The Space Weather Forecast Center – Boulder, Colorado

Particles undergo intense acceleration in the magnetosphere and this triggers auroral precipitation. Its mechanism is poorly evaluated. We also need to put values on the electromagnetic perturbations that cross through the whole of the magnetosphere so as to forecast the scale of polar auroras –which can come down to latitudes as low as Britain– and, in particular, the power of the currents that will be induced in our power networks.

We know very little about the high atmosphere itself. Nowadays, meteorologists are capable of forecasting a snowfall four days ahead, giving the rain-snow limit with amazing accuracy, with a confidence rating of 3 out of 5. It is out of the question to expound on the failures of this science: the know-how used far exceeds that of the poor space meteorologist! We are still quite incapable of predicting, or even giving in real time, details concerning the profiles in altitude of oxygen, nitrogen or hydrogen concentrations and their temperature and velocity. The results would be even more catastrophic if we were asked, at the present time, to describe the profiles of ions and electrons above an altitude of 70 kilometers; they change far too quickly to fit in with existing models.

Furthermore, and this is not the least of our problems, the existing models are research tools and the software packages we use are prototypes. We can only call upon international descriptions of the atmosphere²⁷ based on data from all horizons, and this is totally unsuitable when it comes to describing what is going on above our heads in the most dramatic circumstances.

New instruments of measure must be developed and we need to make progress in the physical comprehension of phenomena by means of the usual osmosis between models and experiments. Observations obtained using satellites and radar must be gathered in international networks; prediction programs must be modeled and optimized and the data made available to all. As far as this subject and others are concerned, physicists must carry on research to further their understanding of the world in which we live. What is more, pretty soon, world leaders, the media and others will fail to understand why we cannot tell them immediately if index 225 X of a magnetic storm will vary within the next hour from 57 to 58. Well, will it?

²⁷ The model usually used by scientists is called MSIS. It was developed by an American team but with international collaboration. Space agencies use their own models.

3.3. TOWARD MATURITY: THE INTENSE SPACE WEATHER STORMS OF OCTOBER-NOVEMBER 2003

The space weather event that so many of us –as researchers– were secretly expecting happened in Fall 2003... At the beginning of October, the Sun still exhibited a regular behaviour, with a monthly smoothed sunspot number in uniform decline since it reached its maximum in April 2000 at 120.8.

A first active region emerged rapidly near the southeast limb of the Sun on October 18th. The Space Environment Center based in Boulder, Colorado, under the supervision of the NOAA, the National Ocean and Atmosphere Agency, is staffed by more than 70 people and is operational 24 hours a day, 7 days a week. Amongst the different warning centers, it constitutes the most important in the world. Its forecasters gave the number 484 to this active region. It was of little concern because of its location. However, on October 22th, it was the source of a strong coronal mass ejection directed at the Earth, which resulted in a warning forecast. The coronal mass ejection impacted our planet the 24th at 15.30 UT, creating a strong geomagnetic storm.

At the same time and by pure coincidence, NASA published the story of an historical solar event that occurred in 1859. It created some confusion in many minds. At the Wall Street stock exchange, several companies involved in space activities suffered a sell off of their stock!

Region 484 was not the only one under watch. Indeed, the solar physicists have made it possible to observe the effects that active regions behind the Sun have on the dark sky. With this method, it is possible to guess in advance new active structures. Between October 18th and 22th, such an active region was detected behind the east limb. It had already produced four coronal mass ejections when it became visible on October 22th. It was given number 486 by the SEC forecasters. Because of its location on the Sun's surface, the SEC Space Weather Advisory issued an alert on a prolonged period of solar activity, followed by several regional warning centers.

Region 486 was approaching the disk center, producing flare after flare: 9 in about one week! Its size exceeded 13 Earth diameters. At the same time, a new active region named 488 appeared near the disk center, leaving the observers with a very crowded Sun.

On October 28th, at 11.10 UT, a major flare occurred above the active region 486. After 8 minutes, the effects of its radiation on the Earth was noticed: HF radio communication blackout on most of the sunlit side of Earth for 1 to 2 hours, errors in positioning. **At high latitudes, sumptuous polar lights occurred.** Shortly after occurred a very fast CME, the fourth most intense since 1976, when space observations began. The solar wind travels at a mean velocity of 370 km/s. As stated in chapter 1 (see table 1.4), the usual high velocity is 950 km/s. This time, we experienced a velocity of ... 2,125 km/s, i.e. 7.25 million kilometers per hour, faster

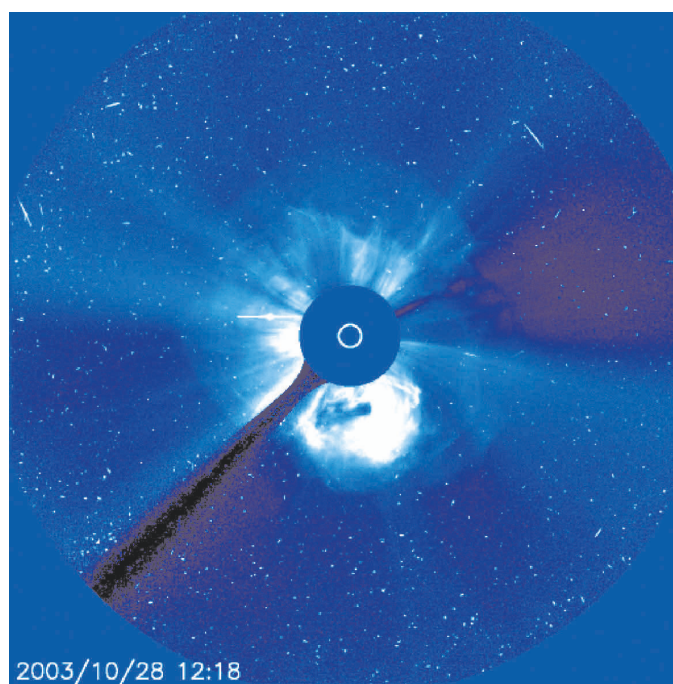


Figure 3.27 - LASCO observes CME on October 28th
Look how it affects the whole corona (credit LASCO/SOHO).

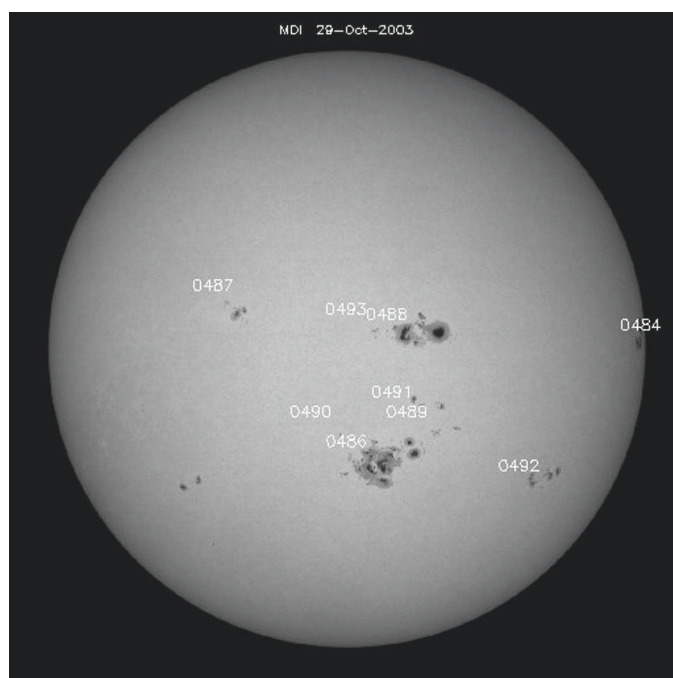


Figure 3.28 - The sun as seen by the MDI instrument on October 29th 2003
The numbering is from the SEC forecasters (credit MDI/SOHO).

than the Bastille Day event seen in chapter 1. By "chance" (chance for the scientists only), it was directed toward the Earth. It arrived on October 29th around 6.00 UT, after a fast 19 hour journey, producing an extremely strong geomagnetic storm that lasted for 27 hours. This was the sixth most intense storm on the record since 1922.

It would have been a major event in Space Weather by itself. However, less than one day later a second Earth directed eruption occurred from the same region. The velocity of its wind was still very respectable: 1,948 km/s (7 million km/h). It arrived at Earth on October 30th at 19.50 UT, creating a 24 hour geomagnetic storm.

In the following days, region 486 gave birth to several other eruptions. The one that occurred on November 4th at 19.50 UT is remarkable. It produced the most intense flare on record. However, the Sun had rotated in the meantime so that the associated CME was directed away from the Earth.

A very large number of scientific instruments were on alert. All the warning centers were working 24 hours a day. Such events are so rare that forecasters had to correct manually the computed geophysical indices in order to describe the reality. This proves the importance of the human expertise. In the Helios center (Lund, Sweden), in the RWCW center (Warsaw, Poland), in RAL (Didcot, UK), in SEC (Boulder, USA) and in all other space weather laboratories, researchers were awake, continuously checking the solar and space situations or ... answering the journalists. They had of course notified power grid customers or space agencies of the imminent threat. This resulted in the fact that almost 25% of the Earth and space science space missions took protective actions that could consist in turning off the instruments. This was a wise choice: about 60% of these space missions experienced effects from this activity. Unfortunately, not all recovered. ADEOS 2, a Japanese spacecraft, was lost. It was devoted to climate change studies. It is not sure yet whether its loss was totally, partially, or not due to the solar activity. Its cost was 512 million euros.

The Advanced Composition Explorer (ACE, NASA) is an Explorer mission. It is devoted to the measurements of the stream of accelerated particles arriving from the Sun and from interstellar and galactic sources. ACE can provide an advance warning (about one hour) of geomagnetic storms that can overload power grids, disrupt communications on Earth, and present a hazard to astronauts. It is scheduled to maintain an orbit between the Sun and the Earth until about 2019. It carried six high-resolution sensors and three monitoring instruments. One was lost during the October 2003 events.

These two cases are only some of several tens that were declared. Hundreds of alerts were released all over the globe. SEC itself issued 278 of them. As a result, airliners rerouted several flights that took polar routes. For the first time ever, the US federal aviation administration issued an advisory to warn that flights travelling north and south of 35° could be subjected to excessive radiation doses. The crew of expedition 8 onboard the International Space Shuttle was told to stand in the most protected part of the station. The troubles in GPS signals resulted in postponed

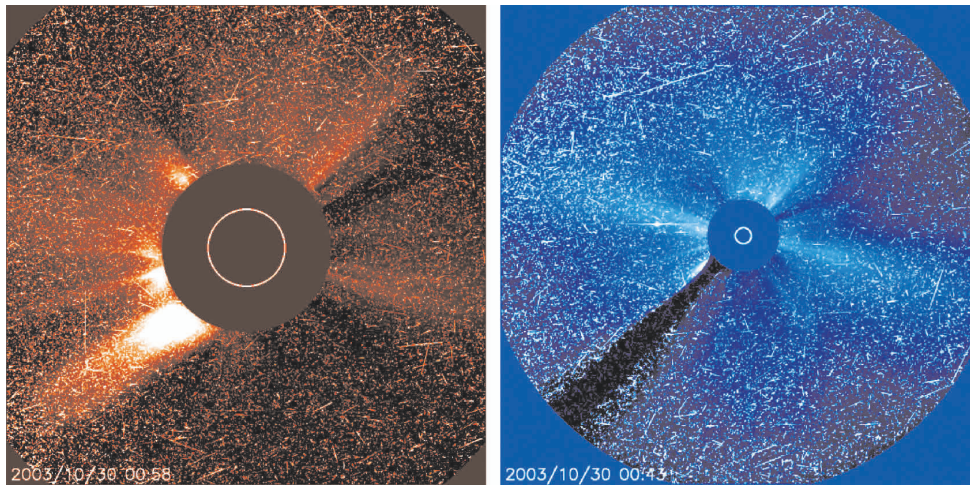


Figure 3.29 - The LASCO coronagraphs are totally saturated when the particles due to the solar flare reach the detectors (credit LASCO/SOHO)

airborne and marine survey operations as well as cancellation of drilling operations. Electricity companies also suffered from the magnetic storms and Ground Induced Currents. Some transformers had to be cooled down. The city of Malmö, Sweden experienced a power system failure on October 30th due to the tripping of a 130 kV power line. The outage time ranged from 20 to 50 minutes and 50,000 customers were affected. However, thanks to the receptiveness of the Swedish space weather scientists, the damages were limited. Shortly after, the Swedish power industry organization ELFORSK acknowledged them. Actions to reduce the power were taken in at least 13 nuclear power plants in the US.

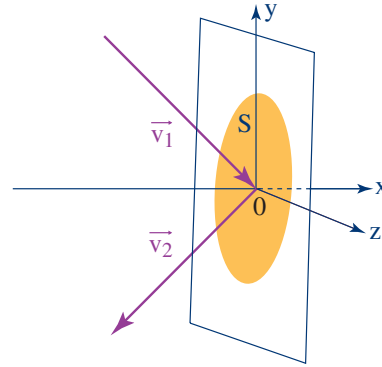
This series of solar events is still under study. Many lessons need to be learned from it, from the scientific point of view as well as from an operational one. However, it demonstrated for the first time the usefulness of the operational space weather warning centers, and certainly was of great help toward the maturity of this field.

APPENDICES

Appendix 1

THE DENSITY AND KINETIC ENERGY OF A GAS

It is possible to relate the pressure, the temperature and the mean kinetic energy of a gas. We shall first study the relationship between the pressure and the kinetic energy in the simple case of the ideal gas. Let us consider the interaction between a gas particle and a surface that defines the volume of the gas. The impacts between the gas particles and the surface are supposedly perfectly elastic (without loss of energy). A particle that hits the surface at a velocity $\vec{v}_1$ leaves it at velocity $\vec{v}_2$ so that $v_{2x} = -v_{1x}$, $v_{2y} = v_{1y}$ and $v_{2z} = v_{1z}$. The variation of the quantity of movement of the particle in the impact is $2m v_x$ (m is the mass of the particle and v_x the norm of v_{1x} and v_{2x}). According to the fundamental equation of the dynamic, surface S on which the impact occurs undergoes, during the impact δt a force F_x along the normal Ox to the surface, so that:



$$F_x \delta t = 2m v_x$$

If n is the number of particles per unit of volume and if the v_x value is the same for all the particles, then the number of impacts on the colored surface S during δt is:

$$\frac{n S v_x \delta t}{2}$$

This number corresponds to the particles found in the cylinder of base S and height $v_x \delta t$. The division by 2 stems from the fact that, in a gas in equilibrium, the particles leave in an identical manner in all directions. Therefore we find the same number of particles going toward the negative x as we do going toward the positive x and here we are only concerned with the latter. The pressure per unit of surface is:

$$P = n m v_x^2$$

Obviously the particles have not the same velocity and this fact is taken into account by considering the average of these forces, therefore the average of v_x^2 , i.e. the mean quadratic velocity $\overline{v_x^2}$.

Thus, the pressure of a very great number of particles N in a volume V is written:

$$P = \frac{N}{V} \left(m \overline{v_x^2} \right) = \frac{1}{3} \frac{N}{V} \left(m \overline{v^2} \right)$$

Since, if v is the velocity of the particles, on average the components following the three directions Ox , Oy , Oz respect an isotropic distribution, and:

$$\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2} = \frac{\overline{v^2}}{3}$$

which can be written finally:

$$PV = \frac{N}{3} m \overline{v^2} = \frac{2}{3} \left(N m \frac{\overline{v^2}}{2} \right) = \frac{2}{3} U$$

where U is the mean kinetic energy of the totality of the particles, i.e. the internal energy of the system. Here we have not taken into consideration contributions to the internal energy of the gas due to particle rotation and vibration and interaction between particles but the translation energy considered here fully explains the phenomena with which we are concerned.

To correlate the mean kinetic energy of a particle and the temperature correctly we have to call upon statistic mechanics and the Boltzmann law of distribution. This demonstrates the theorem on the equipartition of kinetic energy: "In an equilibrium state, the mean kinetic energy for each molecule is, for each degree of freedom, equal to $\frac{1}{2} k_B T$ " (in the International System, the Boltzmann constant k_B is equal to $1.38066 \times 10^{-23} \text{ J K}^{-1}$; this is the ratio between the constant of ideal gases $R = 8.3145 \text{ J mol}^{-1} \text{ K}^{-1}$ and the Avogadro number $\mathcal{N} = 6.0221 \times 10^{23} \text{ mol}^{-1}$). Since, in a gas at thermodynamic equilibrium, the particles can move in three directions, therefore, with three degrees of freedom, the mean kinetic energy of each molecule is $\frac{3}{2} k_B T$.

By writing the mean kinetic energy of a molecule we get back to the law of ideal gases $PV = \frac{2}{3} \mathcal{N} \left(\frac{3}{2} k_B T \right) = \mathcal{N} k_B T = RT$ (for one mole).

However, above all, we see that a velocity corresponds to a temperature. This correspondence has been demonstrated here using a model that involves a great number of molecules, of particles. Later, when we consider particles that are very isolated in space, in other words, in a context where the idea of pressure is more difficult to grasp, this relation will enable us to relate $\overline{v^2}$ and T very directly. The

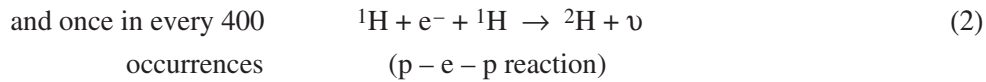
module of the velocity of the particle and the estimated temperature could, for the first approach, still be related by the relation $T = \frac{m \overline{v^2}}{3k_B}$, if the three degrees of freedom are possible.

Appendix 2

THE INTERNAL NUCLEAR PROCESSES OF THE SUN

In the central region of the Sun, the temperature, calculated with the help of classical models, must amount to approximately 15 million degrees and pressure to 221 billion times that of atmospheric pressure. In this region of the core, hydrogen becomes helium by producing energy. This is why the mass proportion of hydrogen is only 40% in the center of the Sun, as opposed to 74% on the surface. The models used at the present time indicate that two cycles of nuclear reaction predominate in these transformations: the proton-proton cycles and the Bethe-Weizsäcker or carbon-nitrogen cycle.

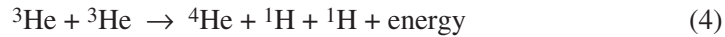
The proton-proton cycle occurs from a temperature of 5 million degrees. It starts by a reaction between electrons and protons, producing atoms of deuterium ^2H , positrons e^+ and neutrinos ν :



Each deuterium unites with a new proton to form helium 3, expressed as ^3He , and a γ radiation:



The ^3He thus formed combines in 91% of cases to produce a nucleus of helium 4, expressed as ^4He , and release protons and a considerable amount of energy (4.2×10^{12} Joule per elementary reaction (4) or 25 megaelectronvolts):



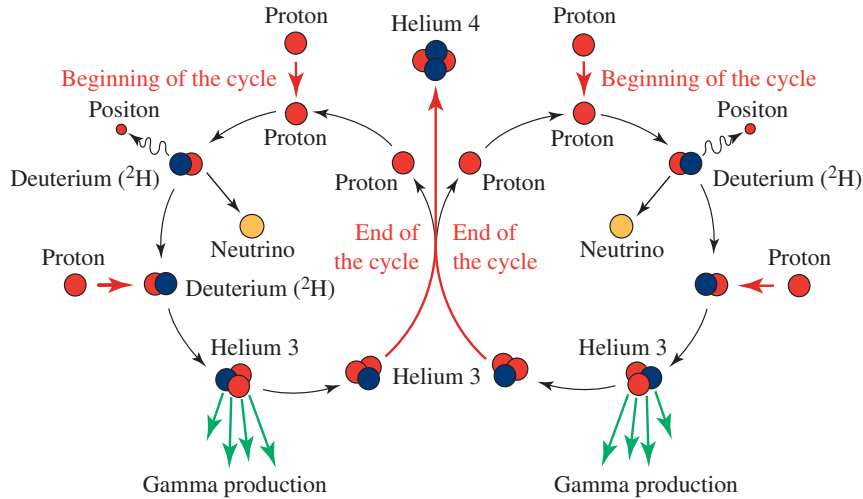
In 9% of cases, helium 3 and helium 4 react to give beryllium and γ rays:



The beryllium then absorbs an electron to form lithium, that is energized in 10% of cases:



In most cases, this lithium then fuses with a proton, producing helium 4 atoms:



The second cycle, suggested by Bethe and Weizsäcker, is also known as the *carbon-nitrogen cycle* since it is implemented by the production of these heavy elements. It can only occur when the temperature exceeds 9 million degrees and is responsible for only a minor part of solar energy. However, it becomes primordial above 16 million degrees, making it the principal source of energy of some stars. It starts with the action of carbon, the residue of the explosion of a supernova, on a proton:



Nitrogen ${}^{13}\text{N}$ is unstable and transforms into carbon ${}^{13}\text{C}$ by losing a positron and a neutrino:



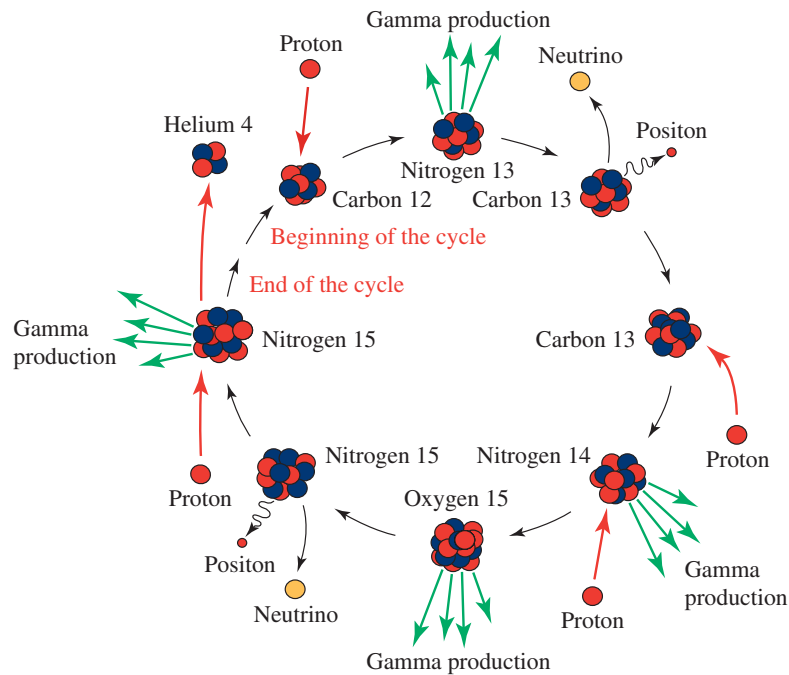
Successive proton captures produce oxygen ${}^{15}\text{O}$:



This unstable oxygen ${}^{15}\text{O}$ dissociates spontaneously into nitrogen ${}^{15}\text{N}$, that fuses with a proton, finally resulting in helium and carbon:



Carbon is, therefore, neither consumed nor produced. In a way, it serves as a catalyst during the Bethe cycle, since it is restored at the end and can be used again. The Bethe cycle can, therefore, be of considerable importance in a star that has very little carbon.



The two cycles take place over very different mean times: 336 million years for the Bethe cycle and 16 billion years for the proton-proton cycle. The reactions are simultaneous; for the Sun, this means a loss of mass of 4.2 million tons per second, transformed into energy. Since it was born, 4.6 billion years ago, the Sun has lost only 3% of its initial mass. The death of the Sun will be due not to this loss of mass but, as described in chapter 1, to the surge of nuclear reactions after hydrogen depletion (in 5 billion years).

Appendix 3

THE ELECTROMAGNETIC FIELD

A **motionless** point electric charge q creates throughout space an electric field $\vec{E}$ ($\vec{E} = \frac{1}{4\pi\epsilon_0} q \frac{\vec{r}}{r^3}$ where ϵ_0 is the dielectric permittivity of the vacuum equal to $8.8542 \times 10^{-12} \text{ F m}^{-1}$ in the International System; $\vec{r}$ defines the point considered in relation to the charge).

A charge q **moving** at velocity $\vec{v}$ creates at all points in space a magnetic field $\vec{B}$ ($\vec{B} = \frac{\mu_0}{4\pi} q \vec{v} \wedge \frac{\vec{r}}{r^3}$ where μ_0 is the magnetic permeability of the vacuum equal to $4\pi \times 10^{-7} \text{ H m}^{-1}$ in the International System). This book frequently used the term magnetic field for $\vec{B}$. Strictly speaking, the magnetic field is $\vec{H}$ and $\vec{B}$, the magnetic induction, is equal to $\mu_0 \vec{H}$ in a vacuum. However, the distinction between $\vec{B}$ and $\vec{H}$ is important only in magnetized condensed matter, and this incorrect name has become widely used in geophysics.

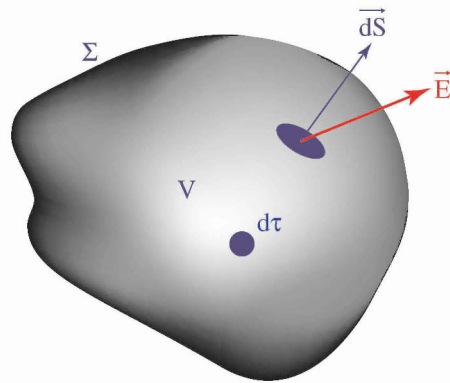
The electromagnetic field is an entity comprising an indivisible electric field $\vec{E}$ and a magnetic field $\vec{B}$. To define this electromagnetic field and its variations it is necessary to be acquainted with the equations of Maxwell that, in a vacuum, are expressed as follows:

$\text{div } \vec{E} = \frac{\rho}{\epsilon_0}$ is the *equation of Poisson*,

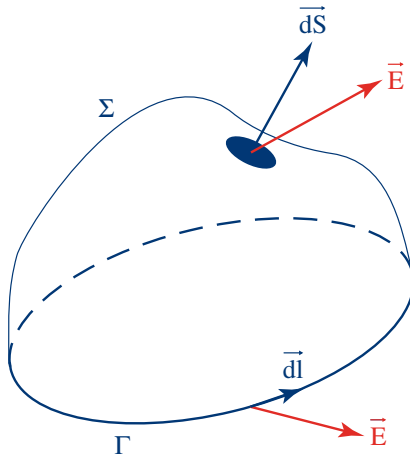
where ρ is the charge density per unit of volume. It is easier to understand its signification using Ostrogradsky's theorem:

$$\iiint_V \text{div } \vec{E} d\tau = \iint_{\Sigma} \vec{E} \cdot d\vec{S}$$

This states that the flux of a vector $\vec{E}$ through a closed surface Σ is equal to the integral of the divergence of the vector in each small volume $d\tau$; this integral is



calculated over the whole of volume V surrounded by Σ . In the case under consideration, this means that if volume V contains no charge ($\rho = 0$), the flux of field $\vec{E}$ through Σ is equal to zero; either $\vec{E}$ is equal to zero or the flux flowing from $\vec{E}$ into V is equal to the flux flowing out. You will have recognized what we also call the Gauss theorem.



$$\overrightarrow{\text{rot } \vec{E}} = -\frac{\partial \vec{B}}{\partial t} \text{ is the equation of Faraday.}$$

Its signification becomes clearer using Stokes' theorem:

$$\iint_{\Sigma} \overrightarrow{\text{rot } \vec{E}} \cdot d\vec{S} = \int_{\Gamma} \vec{E} \cdot d\vec{l}$$

We see that the circulation of the vector electric field $\vec{E}$ along a closed circuit Γ is equal to the flux of vector $\overrightarrow{\text{rot } \vec{E}}$ through any surface Σ resting on Γ .

The equation of Faraday can also be written:

$$\int_{\Gamma} \vec{E} \cdot d\vec{l} = \iint_{\Sigma} \overrightarrow{\text{rot } \vec{E}} \cdot d\vec{S} = -\iint_{\Sigma} \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} = -\frac{\partial}{\partial t} \iint_{\Sigma} \vec{B} \cdot d\vec{S}$$

where the flux of $\vec{B}$ through surface Σ is shown clearly. This takes us back to the law of Lenz; this indicates that a variation in a magnetic flux through a surface leads to a difference in electric potential in this circuit. The equation of Faraday is a local equation and, therefore, true at every point. It states that the variation in time of the magnetic field ($\frac{\partial \vec{B}}{\partial t}$ not zero) creates an electric field $\vec{E}$.

$\text{div } \vec{B} = 0$ expresses the conservation of the magnetic flux i.e. if a closed surface Σ is placed in a region of space where there is a magnetic field, the flux of $\vec{B}$ is equal to zero through Σ (in the volume it defines, the same number of field lines enter through Σ as number that leave).

$$\overrightarrow{\text{rot } \vec{B}} = \mu_0 \left(\vec{j} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right) \text{ is the Maxwell-Ampère's theorem, where } \vec{j} \text{ is the density}$$

of the current created by the free electric charges in motion. The first term of the second member corresponds to the classic theorem of Ampère and states that electric charges in motion create a magnetic field. The second term signifies that the modification in time of an electric field creates a magnetic field even if there are no charges in motion in the region of space under observation.

The four equations of Maxwell are used, in addition to the classic relations of vectorial analysis, resulting finally in the following equations:

$$\begin{aligned}\overline{\Delta \vec{E}} - \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} &= \mu_0 \frac{\partial \vec{j}}{\partial t} + \overline{\text{grad}} \frac{\rho}{\epsilon_0} \\ \overline{\Delta \vec{B}} - \mu_0 \epsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2} &= -\mu_0 \overline{\text{rot}} \vec{j}\end{aligned}$$

These equations are significantly simplified if there are no fixed (ρ) or mobile ($\vec{j}$) charges and take the characteristic form of an equation concerning wave propagation at velocity c with $c^2 = \frac{1}{\mu_0 \epsilon_0}$:

The general solution for equations of this type is a typical sinusoidal wave, for instance, for field $\vec{E}$:

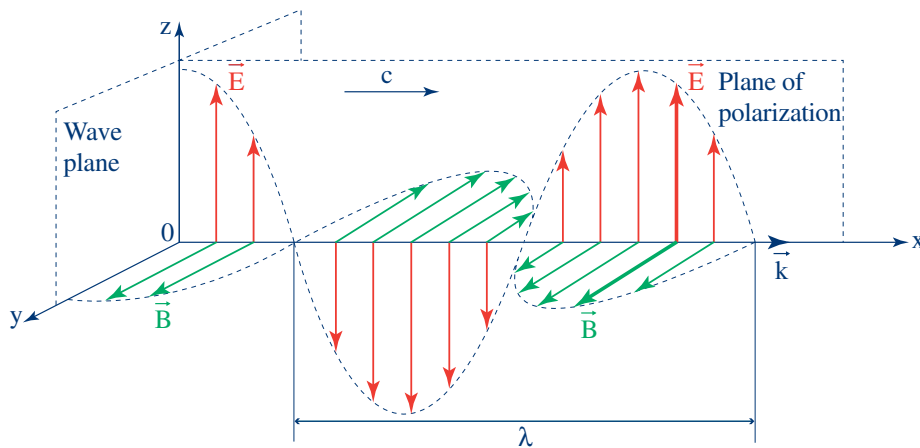
$$\vec{E} = \vec{E}_0 \cos(\omega t - \vec{k} \cdot \vec{r})$$

where ω is the pulsation and $\vec{k}$ the wave vector that defines the direction of wave propagation and whose norm is equal to $\frac{2\pi}{\lambda}$ (λ wavelength). In the very simple case of a propagation that occurs only along a single axis, for instance that of abscissa x , the propagation equations become:

$$\frac{\partial^2 \vec{E}}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad \text{and} \quad \frac{\partial^2 \vec{B}}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 \vec{B}}{\partial t^2} = 0$$

The solutions for $\vec{E}$ and $\vec{B}$, illustrated in the figure, are written:

$$\vec{E} = \vec{E}_0 \cos(\omega t - kx) \quad \text{and} \quad \vec{B} = \vec{B}_0 \cos(\omega t - kx)$$



In the figure, vector $\vec{E}$ is situated in the vertical plane xOz and vector $\vec{B}$ in the horizontal plane xOy . The Maxwell equations in a vacuum enable $\vec{B}$ to be written as a function of $\vec{E}$:

$$\vec{B} = \frac{1}{c} \frac{\vec{k}}{|\vec{k}|} \wedge \vec{E}$$

whence the ratio between B_0 and E_0 can be deduced ($B_0 = \frac{E_0}{c}$). We see that the electromagnetic wave is a transversal wave: the physical quantities that are propagated ($\vec{E}$ and $\vec{B}$) are vectors that are perpendicular to the direction of propagation defined by $\vec{k}$. Furthermore, $\vec{B}$ is perpendicular to $\vec{E}$, since $\vec{k}$, $\vec{E}$ and $\vec{B}$ form a direct trihedron.

Later on we shall remember that $\vec{B}$ and $\vec{E}$ are indissociable and that, in all cases, a displacement of charged particles creates an electromagnetic wave, an electromagnetic field.

Appendix 4

THE DIPOLAR MAGNETIC FIELD

Given particles of various types i.e. electrically neutral, or negatively charged (electrons) or positively charged (ions), in motion. A flux of charged particles q_s at a mean velocity $\vec{v}_s$ can be characterized by a current density $\vec{j}_s = n_s q_s \vec{v}_s$, where n_s is the concentration or number of particles per unit of volume. If several species of particles are involved, the total current density at a point can be written:

$$\vec{j} = \sum_s n_s q_s \vec{v}_s$$

by adding all contributions. In geophysical media, we find primarily neutral plasmas consisting of monocharged ions and electrons. Therefore the concentration in ions and electrons is the same (n_e) and $\vec{j}$ can be written:

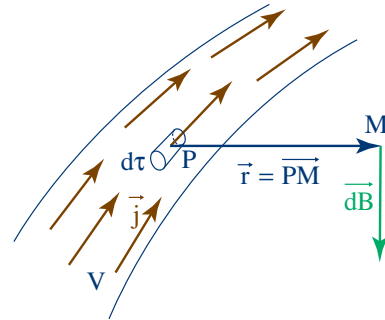
$$\vec{j} = e n_e (\vec{v}_i - \vec{v}_e)$$

where e is the electron charge ($e = 1.6 \times 10^{-19}$ C), $\vec{v}_e$ the mean velocity of the electrons and $\vec{v}_i$ that of the ions (in the simple case where there is just one family of ions). It can be seen that current density is in the same direction as the displacement of the positive ions and reversed in relation to that of the electrons. We shall later keep the notion of current density $\vec{j}$, without forgetting that it is the result of more or less complex displacements of charged particles.

Electric charges create an electric field and electric charges in motion also create a magnetic field. Thus a distribution of current density $\vec{j}$, inside a volume V , creates at all points M of the space defined by its position $\vec{r}$ a field $\vec{B}$ given by the **Biot and Savart law**:

$$\vec{B} = \int_V d\vec{B} = \frac{\mu_0}{4\pi} \int_V \frac{\vec{j} d\tau \wedge \vec{r}}{r^3}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ NA}^{-2}$$

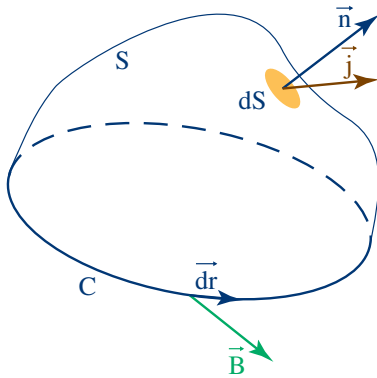


Integration occurs on all the elements $d\tau$ covered by $\vec{j}$ in volume V .

We see that, by definition, $\vec{B}$ does not follow the rules of symmetry of the polar vectors such as $\vec{r}$ or $\vec{j}$. It behaves like an axial vector, for instance, vector $\vec{\omega}$ of the rotation of a solid around its axis.

The Maxwell's equations were introduced in appendix 3. We shall now go back and consider two of them so as to determine the field according to the complexity and the symmetry of a current distribution.

For a start, **Ampere's theorem** enables the magnetic field and current density to be related locally. Ampere's theorem expresses the equality between the circulation of $\vec{B}$ on a closed course C and the flux of the current density vector $\vec{j}$ through any closed surface S that rests on C :



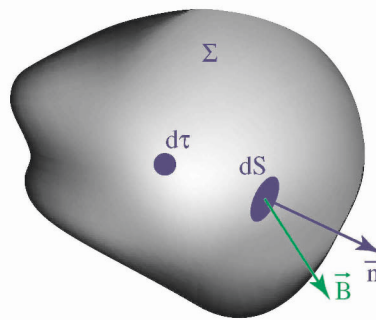
$$\int_C \vec{B} d\vec{r} = \mu_0 \iint_S \vec{j} \cdot \vec{n} dS$$

where $\vec{n}$ is the normal orientated toward a small element dS of S . The vectorial analytic relationship, in particular, Stokes theorem, allows us to write:

$$\int_C \vec{B} d\vec{r} = \iint_S \overrightarrow{\text{rot } \vec{B}} \cdot \vec{n} dS$$

therefore $\overrightarrow{\text{rot } \vec{B}} = \mu_0 \vec{j}$

It is also possible, using Biot and Savarts' law, to demonstrate a second equation, given in appendix 3, that expresses the fact the calculation of flux of $\vec{B}$ through a closed surface Σ gives a zero result (**conservation of the flux**):



$$\iint_{\Sigma} \vec{B} \cdot \vec{n} dS = 0$$

which, using Ostrogradsky's theorem, enables us to write:

$$\iiint_V \text{div } \vec{B} d\tau = 0$$

V being the volume contained in surface Σ . This gives the local equation:

$$\text{div } \vec{B} = 0$$

Once again using the classic vectorial analysis relationships, we can deduce from $\text{div } \vec{B} = 0$ that magnetic field $\vec{B}$ arises from a vector potential $\vec{A}$ so that:

$$\vec{B} = \overrightarrow{\text{rot } \vec{A}}$$

Therefore, to calculate $\vec{B}$ at any point in space, we can execute integrals using the Biot and Savart formula, or use Ampere's theorem, or still vector potential $\vec{A}$ which is generally written:

$$\vec{A} = \frac{\mu_0}{4\pi} \int_V \frac{\vec{j}}{r} d\tau$$

We now have the necessary tools; let us consider the physical case we are often concerned with on the Sun or on the Earth, that of electrical charges following quasi circular paths that are represented by current densities $\vec{j}$ in a closed circuit.

The magnetic moment $\vec{m}$ is defined:

$$\vec{m} = \frac{1}{2} \int_V \vec{r} \wedge \vec{j} d\tau$$

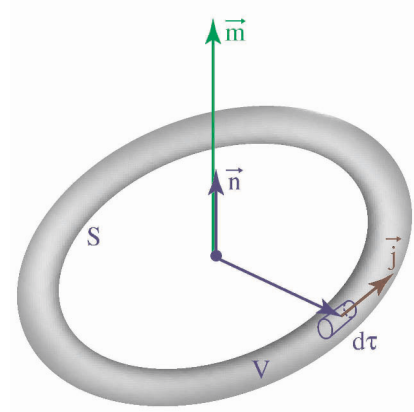
that can be expressed, if we sum up the current distribution, by a filiform current I (with $I d\vec{l} = \vec{j} d\tau$):

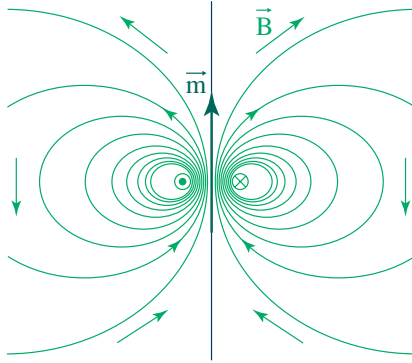
$$\vec{m} = IS\vec{n}$$

S is the surface defined by the current loop and the unitary vector $\vec{n}$ is orientated so that, from $\vec{n}$ we see the current rotating in the trigonometric direction. Using the relations mentioned above, we obtain, from a point M sufficiently distant from the current loop whose position is defined by $\vec{r}$:

$$\vec{A} = \frac{\mu_0}{4\pi} \frac{\vec{m} \wedge \vec{r}}{r^3} \quad \text{and} \quad \vec{B} = \frac{\mu_0}{4\pi} \left[\frac{3(\vec{m} \wedge \vec{r}) \vec{r}}{r^5} - \frac{\vec{m}}{r^3} \right]$$

These formulae are useful for fairly complicated current distribution sets since the integral enabling $\vec{m}$ to be calculated takes it into account. However, the results for $\vec{B}$ and $\vec{A}$ are significant only if $\vec{r}$ is great compared with the dimensions of volume V . In this case, field $\vec{B}$ has a symmetry in a plane passing through $\vec{m}$ and the following figure gives the lines of the $\vec{B}$ field in such a plane. Are represented, in the plane of the figure, the magnetic moment $\vec{m}$ and the intersections of a loop of current that sums up the current distribution.





Field $\vec{B}$, represented in polar co-ordinates, with magnetic moment $\vec{m}$ as its origin, is expressed by its components:

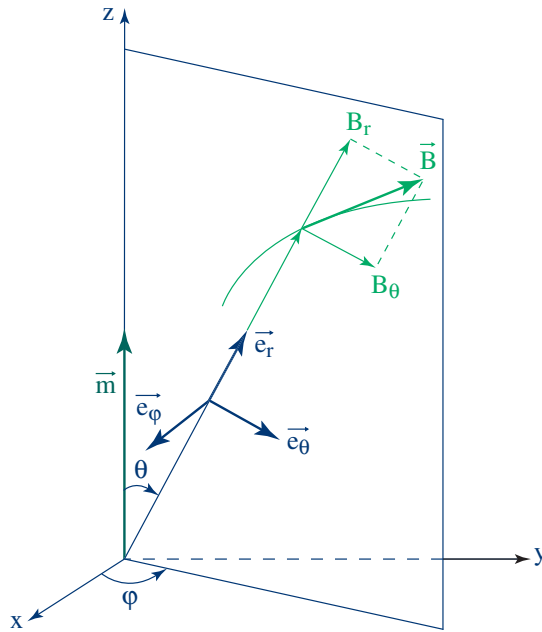
$$B_r = \frac{\mu_0}{4\pi} \frac{2m \cos \theta}{r^3}$$

$$B_\theta = \frac{\mu_0}{4\pi} \frac{m \sin \theta}{r^3}$$

$$B_\phi = 0$$

We see that the module of B is given by:

$$B = \frac{\mu_0 m}{4\pi r^3} [1 + 3 \cos^2 \theta]^{\frac{1}{2}}$$



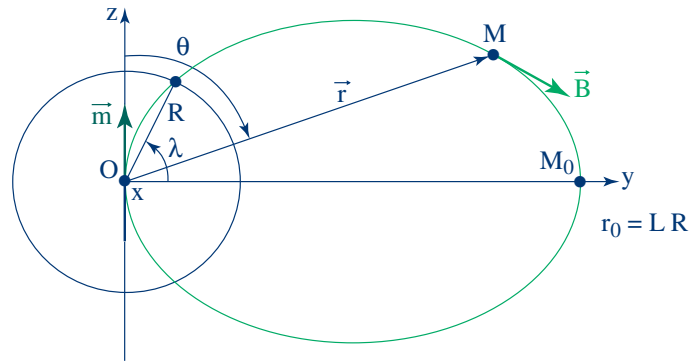
Since $\vec{B}$ is by definition tangential to the field lines, their equation are easily calculated:

$$\frac{r d\theta}{dr} = \frac{B_\theta}{B_r} \quad \text{thus} \quad \frac{dr}{r} = \frac{2 \cos \theta d\theta}{\sin \theta}$$

or by integrating between the value $\theta = \frac{\pi}{2}$ in M_0 and the value of θ in M :

$$\int_{r_0}^r \frac{dr'}{r'} = \log \frac{r}{r_0} = \int_{\frac{\pi}{2}}^\theta \frac{2 \cos \theta' d\theta'}{\sin \theta'} = 2 \log |\sin \theta| \quad \text{thus} \quad r = r_0 \sin^2 \theta$$

r_0 is the distance between the origin and point M_0 where field line $\vec{B}$ cuts plane xOy .



The above results enable the field lines and the magnetic field at the surface of a spherical planet of radius R to be joined. For instance, the field line that passes through the equatorial plane at $r_0 = 4R$ has passed through the surface of the planet at a latitude λ (in the geomagnetic references) so that:

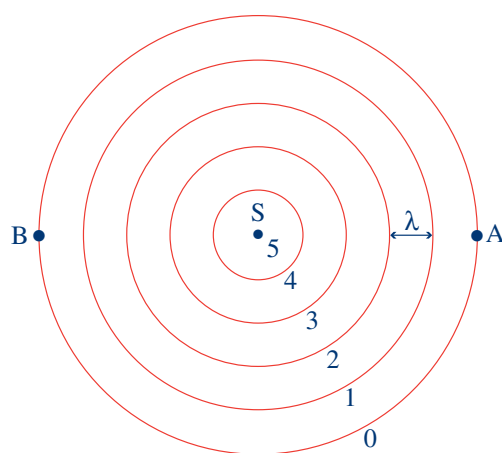
$$R = 4R \sin^2 \theta \quad \text{and} \quad \lambda = 60^\circ$$

We shall use these relations in appendix 14 to describe the magnetic field of the Earth. The most important result is undoubtedly the decrease in $\frac{1}{r^3}$ of the magnetic field $\vec{B}$ created by a magnetic moment. It is the same decrease as that obtained for the electric field created by an electric dipole, whence the name of dipolar field.

Appendix 5

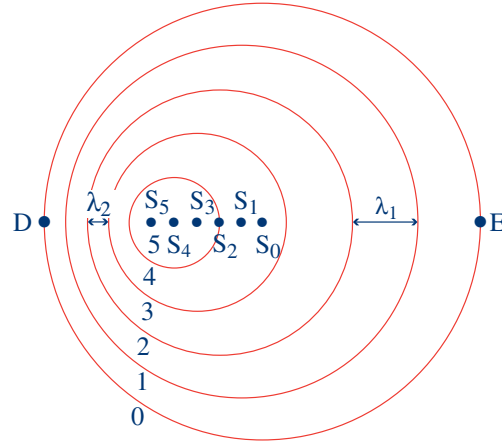
THE DOPPLER EFFECT AND THE WAVELENGTH

We are going to consider a source S of waves. It emits a wave like the one represented in appendix 3 with, just to make it clear, the physical quantity permanently perpendicular to the page and varying in a sinusoidal manner: at times the amplitude is maximum toward us, then it decreases until it cancels itself out, becomes maximum toward the back of the page, cancels itself out again and becomes maximum toward us again. We shall consider that the position "maximum toward us" enables us to see when the wave is coming forward.



In the figure above, source S is immobile and has been emitting since time $5T$ (T being the period of the wave). In the figure we have represented the points where the maximum values of the physical quantity directed toward us can be found (they are circles, traces of spheres on our page. Why spheres? Because the media is isotrope and therefore the wave moves at the same velocity in all directions). The reference wave emitted at $t = 0$ is now at a distance $c \times 5T$, i.e. $5cT$ or 5λ , that is, on a sphere with a radius of 5λ . We have represented the intersection of this sphere and the page by the circle marked 0. The wave emitted at $t = T$ is at a distance of

$c \times 4T$, i.e. 4λ (represented by the circle marked 1). In the same way, the small circle marked 4 corresponds to the emission by S at time $t = 4T$ and the wave has had time to cover (at $t = 5T$) distance λ . At $t = 5T$, the source just emits with the quantity maximum directed toward us. In this context, an observer situated at point A receives the information maximum toward us every interval of time T and so can measure the wavelength $\lambda = cT$ which is the same as that emitted by S. An observer situated at point B would obtain the same result.



Now source S moves along the horizontal axis, toward the left at velocity v (on the diagram we have chosen $v = \frac{c}{2}$). The wave emitted at $t = 0$ by S at S_0 with the quantity maximum toward us is now on the circle whose center is S_0 and radius 5λ , marked 0; the wave emitted at $t = T$ when S was in S_1 is on the circle whose center is S_1 and radius 4λ marked 1; the wave emitted in $t = 4T$ is on the circle whose radius is λ and center S_4 and source S situated at S_5 is emitting with a maximum amplitude directed toward us. An observer situated at point E receives the periodic information with a bigger period than that of source S or, as illustrated in the figure, the wave he receives has a wavelength of $\lambda_1 = (c + v)T$ longer than λ . Inversely, the observer situated at point D receives the information more frequently; the wave has a wavelength $\lambda_2 = (c - v)T$ that is shorter than that emitted by S. Therefore, the wavelength observed decreases if the source is coming toward the observer and increases if the source is moving away. We obtain:

$$\lambda_1 = cT + vT = \lambda + vT \quad \text{and} \quad \lambda_2 = \lambda - vT$$

therefore $\Delta\lambda = \lambda_{\text{observed}} - \lambda_{\text{emitted}} = vT$, v being positive if the source is moving away from the observer.

$\Delta\lambda$ is positive or negative depending on the direction in which the source is moving. We see that this property allows us, by studying the variation in frequency or in wavelength of a wave emitted by a known source in motion, to find the variations in its velocity.

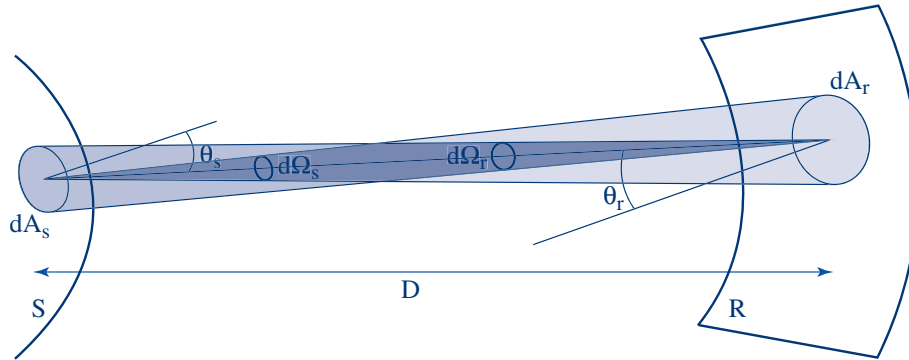
***N.B.** – The presentation of the Doppler effect is right if the phenomenon described acoustic waves. It can be generalized in the case of electromagnetic waves with particular precautions (relativist correction).*

Appendix 6

PHOTOMETRIC QUANTITIES

Photometry is the measurement of energy emitted, propagated and received in the case of radiating phenomena. Photometric quantities are defined using the light ray model: it is considered that the flux of energy per unit of time d^2F (in Watts) emitted by an element dA_s from source S and received by a surface dA_r of a receiver R, is proportional to a property called luminance L and to the optical range d^2G :

$$d^2F = L dA_s \cos \theta_s \frac{dA_r \cos \theta_r}{D^2} = L d^2G$$



with

- ♦ θ_s, θ_r the angles between the straight line that joins the centers of surfaces dA_s, dA_r and the normal of these surfaces;
- ♦ D the distance between dA_s and dA_r . We can define the solid angles $d\Omega_s$ and $d\Omega_r$, under which dA_r and dA_s can be seen respectively:

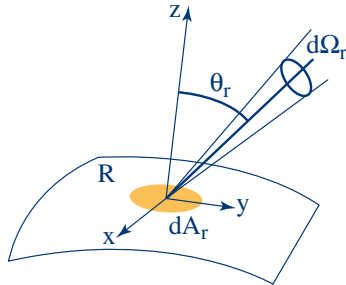
$$d\Omega_s = \frac{dA_r \cos \theta_r}{D^2}$$

in the same way

$$d\Omega_r = \frac{dA_s \cos \theta_s}{D^2}$$

Luminance L is a local measurement of flux density. It is a power per unit of surface and per unit of solid angle; it is expressed in Watts per square meter and per steradian ($\text{W m}^{-2} \text{sr}^{-1}$). All other photometric magnitudes are deduced from L, as shown hereafter.

Brightness

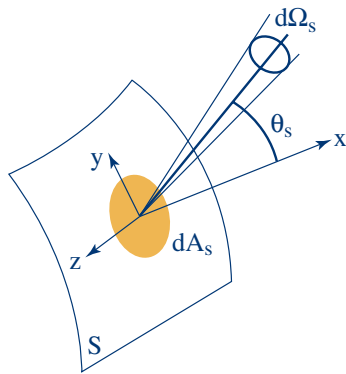


Power received per element of surface of the receiver:

$$E(x, y) = \int L_r(\theta_r) \cos \theta_r d\Omega_r \quad (\text{W m}^{-2})$$

for dA_r .

Emittance

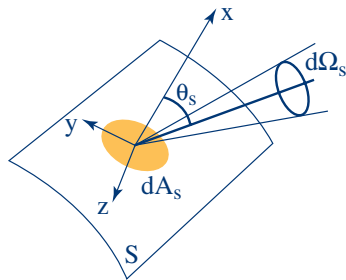


Power emitted per element of surface of the emitter:

$$M(y, z) = \int L_s(\theta_s) \cos \theta_s d\Omega_s \quad (\text{W m}^{-2})$$

for dA_s .

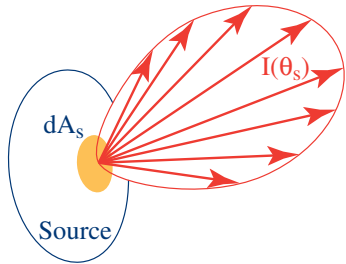
Intensity



Total power emitted by the source in a given direction :

$$I(\text{direction angle}) = \int L(y, z) \cos \theta_s dA_s \quad (\text{W sr}^{-1})$$

for dA_s .



The area constituted by the whole of the extremities of the vector of intensity $\vec{I}$ is called the **intensity indicator**.

These quantities can be found in all the notices pertaining to optical instruments, with various units that can be classified as shown in table 6.1.

Table 6.1 - Quantities and units

Magnitude		Unit e	Unit p	Unit ℓ
Flux F		watt (W)	photon s ⁻¹	lumen (ℓ m) 1 ℓ m = 1 cd sr
Luminance (radiance)	$L = \frac{d^2 F}{dG^2}$	W m ⁻² sr ⁻¹	s ⁻¹ m ⁻² sr ⁻¹	cd m ⁻² = nit
Brightness (irradiance)	$E = \frac{dF_r}{dA_r}$	W m ⁻²	s ⁻¹ m ⁻²	ℓ m m ⁻² = lux
Emittance (excitation or emission)	$M = \frac{dF_s}{dA_s}$	W m ⁻²	s ⁻¹ m ⁻²	ℓ m m ⁻²
Intensity	$I = \frac{dF_s}{d\Omega_s}$	W sr ⁻¹	s ⁻¹ sr ⁻¹	candela (cd)
Amount of light (luminous energy)	$\theta = \int F dt$	joule (J)	number of photons	ℓ m s ⁻¹
Exposure	$\xi = \int E dt$	J m ⁻²	m ⁻²	lux s

Several types of units are used:

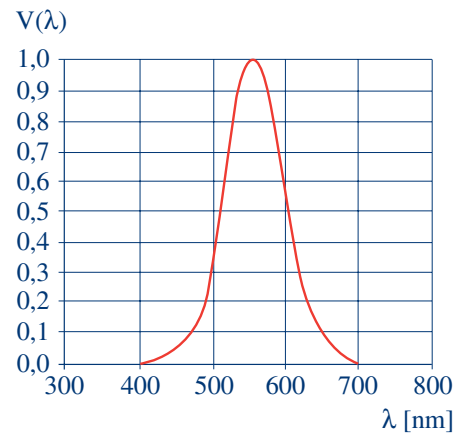
- ♦ units from the usual International System, often expressed with index e (for energetic);
- ♦ units known as photonic (p) where photons are counted but not their energy. These units are used by scientists working with very low radiation fluxes; they are used to count photons of a specific wavelength that is already known;
- ♦ light units that express the sensations perceived by the human eyes (index ℓ or index v for luminous or visual). The luminous values (ℓ or v) are determined in relation to spectral distribution in IS units (index e) as a function of the response curve of the eye. For instance, a very intense luminous source in the ultraviolet or in the infrared will give no value in luminous units. Let us first give the response curve of the eye in intense light (photopic curve). By agreement, what is known as luminous photopic efficiency is represented by the non-dimensional quantity V that varies between 0 (no visual sensation) and 1 (maximum sensitivity of the eye).

We see that the eye is very sensitive to wavelengths of approximately 0.56 micrometers, i.e. in the green-yellow range. The quantity in visual units can be deduced from the energetic one by multiplying the latter by $V(\lambda)$ and by a coefficient that depends on the unit selected.

Table 6.2
Luminous photopic efficiency of the eye

Wavelength (nm)	Luminous photopic efficiency of the eye $V(\lambda)$
380	0.00004
390	1.00012
400	0.0004
410	0.0012
420	0.0040
430	0.0116
440	0.023
450	0.038
460	0.060
470	0.091
480	0.139
490	0.208
500	0.323
510	0.503
520	0.710
530	0.862
540	0.954
550	0.995
555	1.000
560	0.995
570	0.952
580	0.870
590	0.757
600	0.631
610	0.503
620	0.381
630	0.265
640	0.175
650	0.107
660	0.061
670	0.032
680	0.017

**Photopic curve
of the human eye**



For instance, brightness E_e in Watts per square meter (unit of energy) and brightness E_v in lux (unit of light) are connected by the relation:

$$E_v = K_m V(\lambda) E_e$$

$V(\lambda)$ is therefore without dimension and varies between 0 and 1, whereas K_m , the coefficient that varies according to the units selected, amounts to 683 lumen per Watt for photopic vision. Thus, the brightness of the Sun on a plane at sea-level, that is approximately 10^3 W m^{-2} , is equal, at maximum sensitivity of the eye, to 6.83×10^5 lux.

Appendix 7

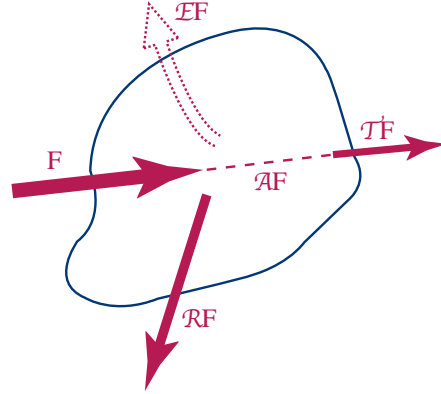
THE BLACKBODY

When a body receives radiation of wavelength λ , and flux F (in Watts), one part, $\mathcal{R}F$ is reflected, one part, $\mathcal{A}F$ is absorbed and one part, $\mathcal{T}F$ is transmitted as schematized in the figure. Coefficients $\mathcal{R}$, $\mathcal{A}$ and $\mathcal{T}$ are, of course, non-dimensional, comprised between 0 and 1, so that:

$$\mathcal{R} + \mathcal{A} + \mathcal{T} = 1$$

so that the energy per second is conserved.

The body also emits a flux $\mathcal{E}F$ by radiation. If the body is in thermal equilibrium with the medium that surrounds it, $\mathcal{A}$ and $\mathcal{E}$ will inevitably be equal. If the body absorbs the totality of the flux (if $\mathcal{A} = 1$) it neither reflects nor transmits the radiation received. Therefore, for this radiation of wavelength λ , it appears to be black. If it is in thermal equilibrium, the body re-emits the totality of what it has absorbed. This is why this "black" body is sometimes called an integral radiator. The "blackbody" is used as a reference in relation to other bodies since it is possible, using statistic thermodynamics, to know the energy density it emits for a fixed wavelength λ .



Here we give the result due to PLANCK in terms of spectral luminance i.e. the luminance of the blackbody in a very small wavelength interval $L'(\lambda) = \frac{\partial L}{\partial \lambda}$.

Planck's formula is written:

$$L'(\lambda) = \frac{2hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda k_B T}} - 1 \right)}$$

with $h = 6.6256 \times 10^{-34}$ Js Planck's constant,

$k_B = 1.38054 \times 10^{-23}$ JK⁻¹ Boltzmann's constant,

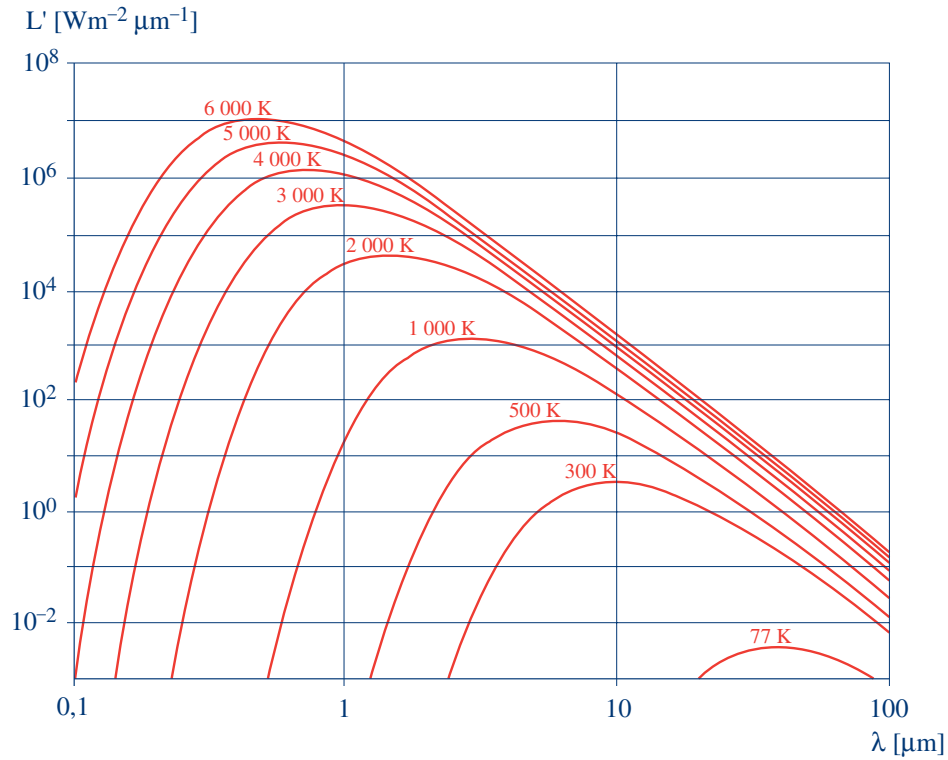
and $c = 2.998 \times 10^8$ m s⁻¹ the velocity of light in vacuum.

When wavelength λ is very small, i.e. when $\frac{hc}{\lambda}$ is high compared with $k_B T$ we have what is known as Wien's formula:

$$L'(\lambda) = \frac{2hc^2}{\lambda^5} e^{-\frac{hc}{\lambda k_B T}}$$

and when, on the contrary, λ is high ($\frac{hc}{\lambda}$ small compared with $k_B T$) we have what is known as Rayleigh's formula:

$$L'(\lambda) = \frac{2c k_B T}{\lambda^4}$$



The remarkable property of the emission of the blackbody is illustrated by the above figure: the spectral luminance of the blackbody varies in function of the wavelength, with the temperature being the sole parameter. Thus, a black body in thermal equilibrium is at maximum emission for a defined wavelength with the numerical values of k_B and c previously recalled by the relation:

$$\lambda_{\max} = \frac{2898}{T} \mu\text{m}$$

This property is of utmost importance since, by studying a source near to the blackbody in function of wavelength, it is possible to know its temperature. If we remember that the Sun behaves in almost the same way as a blackbody, we can see just how important this result is.

It is also possible to consider the totality of the flux emitted by the blackbody by calculating the total luminance $\int_{-\infty}^{+\infty} L'(\lambda) d\lambda = L_{\text{totale}}$ and to deduce the total emittance and, therefore, the totality of the flux emitted per unit of area of the source, for all wavelengths. We find the Stefan-Boltzmann law:

$$M_{\text{totale}} = \frac{2\pi^5 k_B^4 T^4}{15c^2 h^3} = \sigma T^4$$

with $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ T}^{-4}$.

Once again, we see how greatly the emission of a blackbody depends on its temperature.

Appendix 8

A COMPREHENSIVE VIEW OF ELECTROMAGNETIC WAVES

The wave-corpuscle duality makes it possible to use either the concept of the electromagnetic wave or that of the photon. Thus a wave of frequency ν , or wavelength λ (with $\nu = \frac{c}{\lambda}$) can also be considered as a particle flux of energy E :

$$E = h\nu = h \frac{c}{\lambda} \quad (\text{h is the Planck constant})$$

The nature of electromagnetic waves –indissociable electric and magnetic fields– was described in appendix 3. Below we give a very rapid description of these waves, with a few remarks concerning the various wavelengths. The creation, the reception and, therefore, the effects and utilization of the waves can be grasped perfectly by taking into account the values of the wavelengths λ and the frequencies ν for high values of λ . The energies of the photons (expressed here in electronvolts), make it possible to understand the nature for low values of λ .

Table 8.1 - Range of radio waves

Radio waves	$\Delta\lambda$	$\Delta\nu$
ULF	$> 3 \times 10^7$ m	< 10 Hz
ELF	3×10^7 m to 100 km	10 Hz to 3 kHz
VLF	10 km to 100 km	3 kHz to 30 kHz
LF	1 km to 10 km	30 kHz to 300 kHz
MF	100 m to 1 km	300 kHz to 3 MHz
HF	10 m to 100 m	3 MHz to 30 MHz
VHF	1 m to 10 m	30 MHz to 300 MHz
UHF	10 cm to 1 m	300 MHz to 3 GHz
SHF (micrometric waves)	1 cm to 10 cm	3 GHz to 30 GHz
EHF	1 mm to 1 cm	30 GHz to 300 GHz
submillimetric waves	0.3 mm to 1 mm	300 GHz to 1 THz

These waves start with very long wavelength values on with a human scale: several thousand kilometers for ULF (ultra low frequencies). Then we pass through the "extra low frequencies", the "very low frequencies" and the "low frequencies". These waves are used in telephony (by carrier currents) and for sounding defects in solids. We are well acquainted with very low frequencies (VLF) in induction heaters and radio-navigation, low frequency waves (LF) also in radio-navigation and broadcasting. Our radio sets have accustomed us to medium waves (with amplitude modulation) and short waves or high frequencies (with frequency modulation). Very high frequency waves (VHF) are used for both radio and television broadcasting. Next we find the range of micro-waves; their names clearly indicate the typical wavelength values: decimetric waves used for television and radar systems (L band), centimetric waves for radar (S, C, X, K bands) and masers that also use millimetric waves. The waves described above are represented ideally in their creation and reception by the wavelength: television aerials on roofs measure between 50 centimeters and 1 meter, giving an idea of the wavelengths used.

Table 8.2 - From infrared to γ rays

Radiation		$\Delta\lambda$	Energy (eV)
Infrared	Remote	10^4 nm to 10^6 nm	1.24×10^{-3} to 0.12
Infrared		700 nm to 10^4 nm	0.12 to 1.77
Visible		400 nm to 700 nm	1.77 to 3.1
Ultraviolet		30 nm to 400 nm	3.1 to 41.4
	Near	200 nm to 400 nm	3.1 to 6.2
	Distant	120 nm to 200 nm	6.2 to 10.3
	Extreme	30 nm to 120 nm	10.3 to 41.4
	XUV or soft X	10 nm to 30 nm	41.4 to 124.1
X		0.005 nm to 10 nm	124.1 to 2.5×10^5
γ		< 0.005 nm	$> 2.5 \times 10^5$

With infrareds, we enter into the range of electromagnetic waves, the effects of which can be understood by considering the values of both the wavelengths and photon energy ($h\nu$). For instance, infrared radiation can trigger vibrations, and more or less considerable rotation of molecules or molecule systems. It is used for heating, photography (infrared) and is produced by some lasers.

Visible radiation triggers electron jumps from one orbital to another, amongst the electrons that are weakly joined to the atomic nucleus. Their many uses are known in the areas of sight, photography, chlorophyll synthesis, chemical analysis. Then, as photon energy increases, the effects become noticeable on electrons that are increasingly joined to the atomic nucleus. Ultraviolet rays can be very active in

chemical analysis, in reactions and also on our skin on the beach! X-ray photons can trigger energy changes in electrons at levels even closer to the nucleus. Their wavelength is close to that of interatomic distances, whence their use in diffraction to find the interatomic distances. They are also used in medical and industrial radioscopy and to material and surface checking.

As the wavelength decreases, the objects concerned are smaller and photon energy increases, so the effect on matter becomes increasingly intimate. We switch from effects on electrons to others on atomic nuclei, creating isotopes and separating the particles that make up the nuclei (with γ rays). Naturally, the applications involve ions and isotopes.

This overall view of electromagnetic waves is only a cursory glance at 10^{23} magnitudes (of wavelength or frequency). The reader must not be led to think that by regular scanning the waves can be made to scroll continuously if their frequency is made to vary. The creation or reception of electromagnetic waves can only be observed if there is physical interaction between wave and matter at the frequency which interests us. For instance, a wave measuring several Angstrom units (10^{-10} meters) at about 412 kiloelectronvolts has hardly any effect on matter since it is situated between the photo-electric effect and the electron-positron process. However, the energy of these photons created by irradiated sheets of gold is far higher than that of X photons which are quickly absorbed, including by our own body. Photon energy and the power to create an effect must, therefore, not be confused.

Appendix 9

THE MAGNETIC FIELD AND THE MOVEMENT OF PARTICLES, FROZEN PLASMA AND FIELDS

The Sun emits electromagnetic waves and particles that make up the solar wind. Furthermore, the phenomena occur in the solar magnetic field (appendix 4). Magnetic proliferation on the surface of the Sun is due to the movements of ionized matter; moreover, the path of the charged particles is modified in a magnetic field. All this is very complicated, so let us first recall what happens in the simple case of a charged particle moving in a magnetic field.

A particle in motion in a constant magnetic field

Given a particle of mass m and charge q at a velocity $\vec{v}$ in an uniform magnetic field $\vec{B}$. It undergoes a Lorentz force that is written:

$$\vec{F} = q \vec{v} \wedge \vec{B}$$

The reference frame is such that axis z is carried by the magnetic field. By writing the fundamental principle of dynamics projected according to the three coordinate axes:

$$\left\{ \begin{array}{l} m \frac{dv_x}{dt} = q B v_y \\ m \frac{dv_y}{dt} = -q B v_x \\ m \frac{dv_z}{dt} = 0 \end{array} \right.$$

v_z is not affected by the magnetic field and remains equal to the component along z of the initial velocity of the particle. From the first two equations, we deduce that:

$$\left\{ \begin{array}{l} v_y = \frac{m}{qB} \frac{dv_x}{dt} \\ v_x = -\frac{m}{qB} \frac{dv_y}{dt} \end{array} \right.$$

By replacing v_x and v_y by their values in the derivatives we obtain:

$$\begin{cases} \frac{d^2 v_x}{dt^2} = \left(\frac{qB}{m}\right)^2 v_x \\ \frac{d^2 v_y}{dt^2} = \left(\frac{qB}{m}\right)^2 v_y \end{cases}$$

Therefore a particle with a charge q , with an initial velocity v_x that is not equal to zero, will undergo an acceleration along axis x . A force F_y is then created that tends to bring it back to $-y$ (if the charge is positive) or y (negative charge). The result is then a gyration around the z axis, that brings the magnetic field to the angular velocity ω_c , called the **cyclotron angular frequency**:

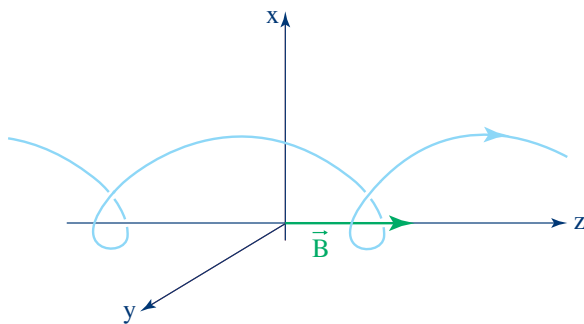
$$\omega_c = \frac{qB}{m}$$

The direction of the gyration (and therefore the sign of ω_c) depends on the sign of the particle but all the particles describe helices of constant pitch, the axis being the direction of the magnetic field (the pitch is determined by the value of velocity v_z along this axis). The movement in the plane perpendicular to this axis is a circular movement at uniform velocity (the magnetic force does not bring any energy to the particle). If we characterize the direction parallel to the field by " $//$ " and any direction in the perpendicular plane by " $\perp$ " (a representation that is commonly used in aeronomy since the direction parallel to $\vec{B}$ is a privileged direction) then the particle velocity in the perpendicular plane has for module:

$$v_{\perp} = \sqrt{v_x^2 + v_y^2}$$

and the radius of the circular path described in the perpendicular plane is written:

$$r_L = \frac{v_{\perp}}{|\omega_c|} = \frac{mv_{\perp}}{|q|B} \quad \text{called Larmor's radius}$$



The path represented corresponds to a particle with a positive charge having, at the initial moment, a component velocity not equal to zero, v_x positive and v_z positive. The latter is conserved in the movement.

The previous relations describe the movement of a charged particle around a center guide, moving at velocity v_z along axis z (direction of $\vec{B}$). However, we know that a charged particle creates a magnetic field. In the present case, the particle(s) in

motion in a plane perpendicular to $\vec{B}$ can be compared to a coil of current with an axis $\vec{B}$. It is easy to verify that the magnetic field created by this coil is the reverse of the original magnetic field $\vec{B}$. This is a general result; gyration is always described in a direction that helps decrease the original magnetic field.

Frozen plasma and fields

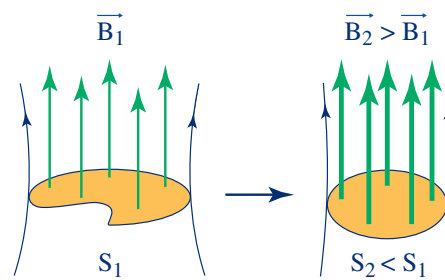
The above example is very simple compared with the phenomena to be modeled: convection movements of plasma create magnetic fields on the Sun with a local North pole and a local South pole. Field lines leave these poles and the charged particles of the plasma wind around these lines. However, the Sun also ejects plasma outward at velocities of 700,000 to 2.5 million kilometers per hour and these particles follow the field lines, winding round them.

In a magnetic field tube, the quantities that interact are the electric field $\vec{E}$, the magnetic field $\vec{B}$, the current density $\vec{j}$, the particle velocity $\vec{v}$, the mass ρ per unit of volume, the pressure p , since this plasma is also a fluid. Generally speaking, therefore, we have to solve a problem with fourteen variables (three per vectorial quantities and two scalar quantities). We have the four Maxwell equations, the energy conservation and the equation pertaining to the state of the plasma. We see that, in the same way as in the previous example, the fields change the trajectories of the particles that "follow" it and that these also create fields. In the case of the Sun, it is impossible to tell which, of the magnetic field (interplanetary) or the plasma in movement (solar wind) triggers the other. The field and the plasma are said to be "frozen". We shall illustrate this phenomenon with a specific example, considering that Ohm's law can be written simply:

$$\vec{j} = \sigma [\vec{E} + \vec{v} \wedge \vec{B}]$$

where σ is the very high conductivity of a plasma with practically no collisions between particles. The higher the value of σ , the closer the term in brackets is to 0.

In such a context, we can calculate the flux of $\vec{B}$ through a surface S_1 in a field tube and see that frozen plasma and flux signifies that a narrowing of the field tube (cross-section of S_1 to S_2) will give rise to an increase in $\vec{B}$ ($\vec{B}_1$ to $\vec{B}_2$) that corresponds to the conservation of the flux. This is what frequently happens in field tubes that are frozen to the solar wind.



Appendix 10

KINETIC PRESSURE AND MAGNETIC PRESSURE

If the solar wind with its particles is assimilated to an ideal gas, the *kinetic pressure* exercised on a surface unit can be written:

$$p_c = \frac{N}{V} k_B T = n k_B T$$

where n is the number of particles per unit of volume, k_B the Boltzmann constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$) and T the absolute temperature. We have already seen in appendix 1 that the energy of the particles can be related to the kinetic energy for each degree of freedom:

$$\frac{1}{2} k_B T = \frac{1}{2} m \overline{v^2}$$

where m is the mass of the particles and v their velocity. In the solar wind, the magnetic stresses illustrated in appendix 9 limit the degrees of freedom to two. Furthermore, since all the particles move at the same velocity in the solar wind, we can neglect the electrons that are 1836 times lighter than the protons and only keep the latter ($m = 1.675 \times 10^{-27}$ kilograms). The kinetic pressure of the solar wind then becomes:

$$p_c = \frac{1}{2} n m \overline{v^2} = n k_B T$$

The *magnetic pressure* can be calculated in various ways, either by considering the forces exercised on the particles gyrating in a helix around the field (like current coils) or by calculating the density of energy per unit of volume. We find a pressure p_m due to these magnetic forces:

$$p_m = \frac{B^2}{2\mu_0}$$

(μ_0 is the permeability of the vacuum $1.2566 \times 10^{-6} \text{ H m}^{-1}$)

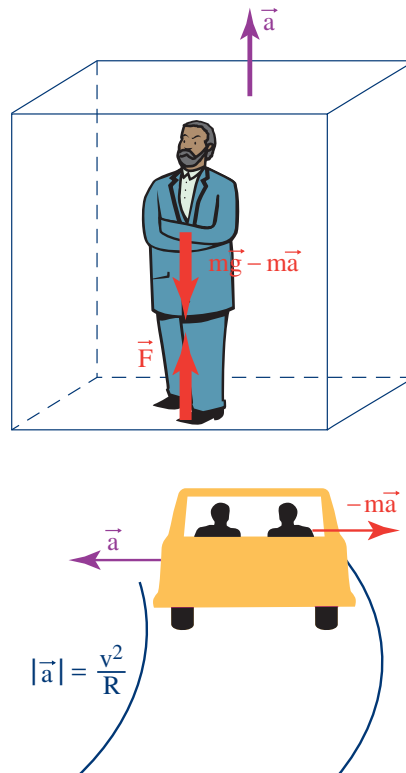
Appendix 11

THE CORIOLIS FORCE

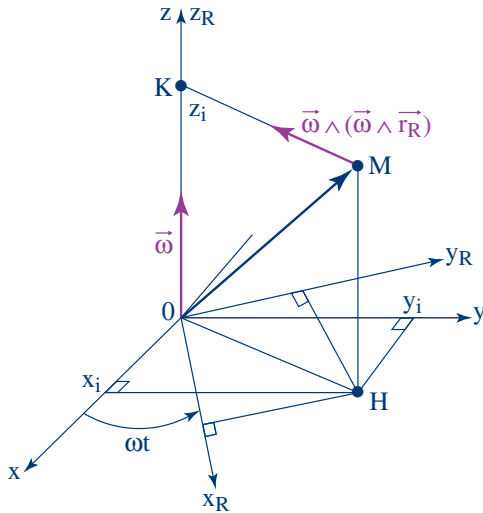
Coriolis' force is a force felt by an observer (or an object) in motion in a system in rotation. This is what is sometimes called a fictitious force and we experience it in many situations. For instance, when an elevator starts to rise, it feels as though you are pinned to the floor and yet you are standing still in the elevator. The elevator is being subjected to an upward acceleration $\vec{a}$, in the reference frame of the apartment block in which it is translating. You are immobile in the elevator because the upward force $\vec{F}$ that you receive via the floor balances out your weight ($m\vec{g}$ if your mass is m and $\vec{g}$ the acceleration of the gravity) and $-m\vec{a}$ the fictitious force that gives you the impression that your weight has increased.

In the same way, when you are sitting in an automobile next to the driver and he veers sharply round a left-hand curve, you are pinned against the right-hand door. Before, when the vehicle was traveling at a constant velocity in a straight line, you were sitting still on your seat and all the forces balanced each other out. During that curve taken at a constant velocity v , the automobile remains on its circular path due to a centripetal acceleration (directed toward the center of the curve of the circular path of radius R) of module $\frac{v^2}{R}$. You then undergo a fictitious force in the direction opposed to module $\frac{mv^2}{R}$.

We have just illustrated this notion of fictitious force in a reference frame in translation in relation to a fixed reference frame, on the one hand, and in a rotating



reference frame in which the object (you) is immobile. What happens when an object is moving at a velocity $\vec{v}_R$ in relation to the rotating reference frame in rotation?



To represent this situation, we take a cartesian reference frame $0x_Ry_Rz_R$, in rotation in relation to a fixed reference frame $0xyz$ (axes $0z_R$ and $0z$ are the same). We consider that the rotation around axis $0z$ takes place with a constant angular velocity ω . We can define the position of a point M by the vector $\vec{OM}$ and write its components in the fixed reference frame in relation to the components (coordinates) in the mobile reference.

We write:

$$x_i = x_R \cos \omega t - y_R \sin \omega t$$

$$y_i = x_R \sin \omega t + y_R \cos \omega t$$

$$z_i = z_R$$

We obtain the velocity then the acceleration by deriving each member, which is easy with trigonometric functions. The equations obtained enable acceleration $\vec{a}$ of M in the fixed reference frame to be expressed as a function of the acceleration $\vec{a}_R$ of M in the rotating reference frame:

$$\vec{a} = \vec{a}_R + \vec{\omega} \wedge (\vec{\omega} \wedge \vec{r}_R) + 2 \vec{\omega} \wedge \vec{v}_R$$

$\vec{\omega}$ is the angular velocity vector, carried by the axis of rotation; $\vec{r}_R$ and $\vec{v}_R$ are the position and the velocity of M in the rotating reference frame. Two terms are added to $\vec{a}_R$ in the second member:

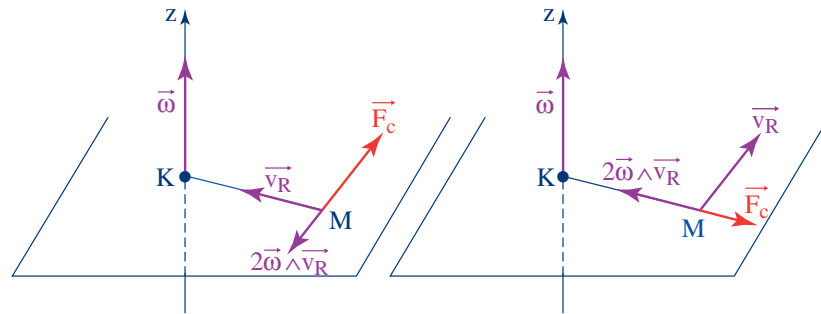
$$\vec{\omega} \wedge (\vec{\omega} \wedge \vec{r}_R)$$

this vector is represented in the figure. It is easy to see that it is directed along $\vec{MK}$ and that its module is $\omega^2 MK$. This is the centripetal acceleration in the example of the automobile taking a curve (with $MK = R$ and $v = \omega R$):

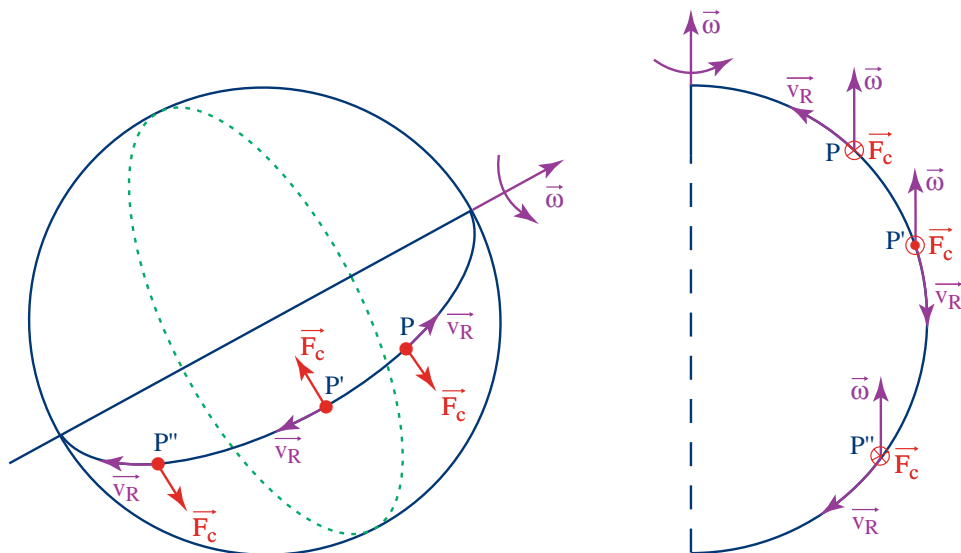
$$2 \vec{\omega} \wedge \vec{v}_R$$

This contribution exists only if M is in motion in relation to the rotating reference frame. However, it is equal to zero if this movement is parallel to the rotation axis and, on the contrary, it is at a maximum, if $\vec{v}_R$ is perpendicular to this axis. In the two examples represented below, $\vec{v}_R$ is in a plane perpendicular to $\vec{\omega}$ (therefore to $0z$) in the case where it is directed toward the axis, in the other case it is perpendicular to MK . In both cases, acceleration $2 \vec{\omega} \wedge \vec{v}_R$ is indicated. If a mass m is placed at

point M, it will undergo a fictitious force $-m(2\vec{\omega} \wedge \vec{v}_R)$ which will deflect the path of object M toward the right (from our position of observation). This fictitious force is the **Coriolis' force** $\vec{F}_c$.

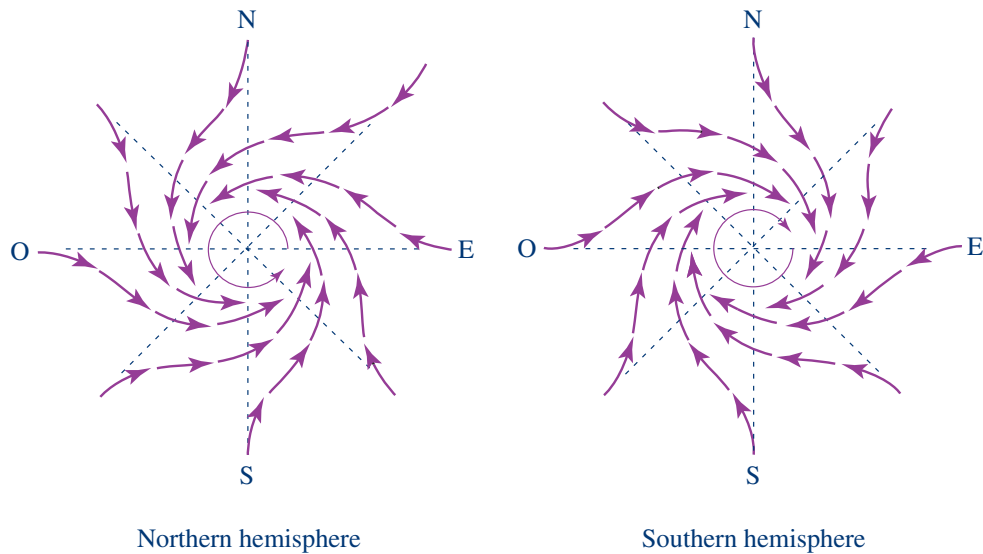


Let us consider an object that moves, along a meridian, in the rotating terrestrial reference frame whose influence it undergoes. We have represented this object on the globe below. At a point P of the northern hemisphere, a particle of relative velocity $\vec{v}_R$ directed northward, undergoes a Coriolis force perpendicular to both $\vec{\omega}$ and to $\vec{v}_R$, directed eastward, that deflects its path. At point P', a particle with a relative velocity directed southward is deflected westward. In the southern hemisphere (point P''), the vectorial product indicates that a particle with a relative velocity $\vec{v}_R$, directed southward, is deflected eastward (figure in perspective on the left and meridian cross-section, on the right).



The Coriolis force is clearly present; this explains the direction in which water empties from a washbasin, why one bank of a waterway erodes more than the other (the right-hand bank in the northern hemisphere) and, of course, the shift in the paths of missiles or shells. In all cases, the rotating reference frame R is the Earth, that rotates on its axis in relation to an observer at a fixed point in the solar system.

The example best adapted to the theme of this book is given on television every evening when the weather of our low atmosphere is presented (not that of space, that will soon come). The air currents are air moving from high pressure zones toward low pressure zones. The wind blows radially toward the center of the low pressures. Coriolis' force deflects the molecules of air toward the right of their path in the northern hemisphere (toward the left in the southern hemisphere). The result is a direct vortex effect (retrograde in the south). Obviously the pressure, the temperature and their various distributions complicate the phenomena, but the drawings below are a good illustration of what we see as cloud swirls. In actual fact, the Coriolis forces applied to the molecules of air are low but they have a permanent action on objects in motion and their effect can, therefore, be considerable.



Appendix 12

KEPLER'S LAWS

The movements of celestial bodies are the consequence of the fundamental laws of dynamics and of the law of gravitation. It was KEPLER who discovered them, using the observations of Tycho BRAHÉ as well as his own. They can be stated as follows:

1. Planets describe an elliptic path with the Sun at one focus. This is the **law of orbits**.
2. A line drawn from the Sun to a planet sweeps out equal areas in equal times. This is the **law of surfaces**.
3. The squares of the period of revolution of the several planets around the Sun are proportional to the cubes of the semi-major axes of the ellipses. This is the **law of periods**.

1. *The first of Kepler's laws* is obtained by calculating the trajectories of a material point subjected to the action of a central force i.e. the action of a force directed toward the same point taken as a center. The calculation shows that the trajectories are situated in a plane and that they are ellipses, parabolas or hyperbolas.

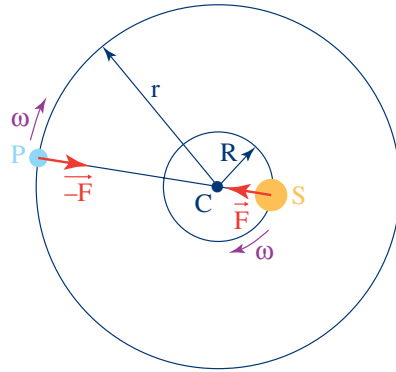
The demonstration is not difficult in the specific case where the planet is a circle. Planet P of mass m describes a circle of radius r around the center of mass C, whereas the Sun of mass M (big compared with m) describes a circle of radius R . By definition of the center of mass m ,

$$MR = mr$$

P and S are subjected to the gravitational forces balanced by the centripetal forces (fundamental law of dynamics for translation):

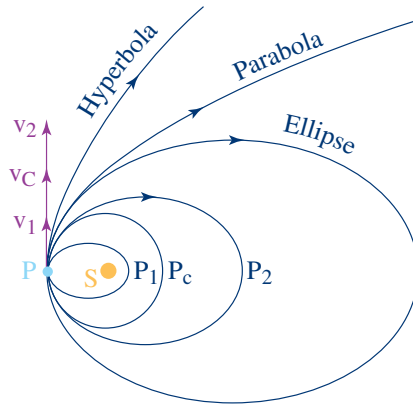
$$\frac{GMm}{(r+R)^2} = m\omega_P^2 r = M\omega_S^2 R$$

We see that the angular velocities are the same (ω) by reason of the relation that defines the mass center.



If the mass of the Sun is very big compared with that of the planet, which is the case, r is very big compared with R and therefore $r + R \approx r$. If the path is a circle (situation P_c), the velocity of the planet, perpendicular to the vector radius, can be written:

$$v_C = r \omega \approx \left[\frac{GM}{r} \right]^{\frac{1}{2}}$$



More complicated calculations show that the nature of the orbit depends on the initial velocity of the planet. If it is less than v_C , the path is an ellipse of which the Sun occupies the most remote center (situation P_1). If the velocity becomes bigger than v_C , the path is still an ellipse of which the Sun occupies the least remote center (situation P_2).

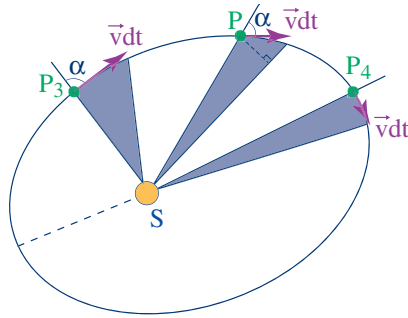
If the velocity reaches value:

$$v_P = \left[\frac{2GM}{r} \right]^{\frac{1}{2}}$$

the path becomes a parabola. If the initial velocity increases further, the path becomes a hyperbola and the celestial body is no longer a planet since it never returns to the same position.

2. The second Kepler's law is obtained by applying the theorem of the fundamental law of dynamics for rotation. Since the gravitational forces are central, their moments in relation to the Sun are permanently zero. The kinetic moment is therefore constant:

$$\overrightarrow{SP} \wedge m\vec{v} = \text{constante} = m r v \sin \alpha$$



In the diagram opposite, the surface scanned by a vector radius SP during time dt is colored. This surface dS tends toward $r v dt \sin \alpha$ when dt tends toward zero. It is therefore possible to conclude that $\frac{dS}{dt}$, the surface scanned by SP per unit of time, is a constant. As a result, during a revolution on the orbit, the planet is at maximum velocity when it nears the Sun (situation P_3) and at minimum velocity when it is far from the Sun (situation P_4).

3. *The third of Kepler's laws* is easily demonstrated in the simple case of the circle with $r \gg R$. The velocity in orbit is equal to the perimeter of the orbit divided by the period of revolution T :

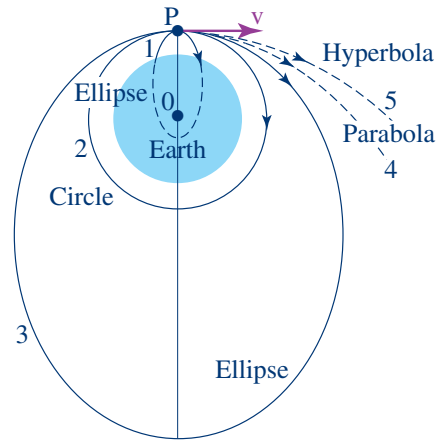
$$v_c = \frac{2\pi r}{T} = \left[\frac{GM}{r} \right]^{\frac{1}{2}}$$

therefore

$$T^2 = \frac{4\pi^2}{GM} r^3$$

Since $\frac{4\pi^2}{GM}$ is a constant in the solar system, we see that T^2 is proportional to r^3 for all the planets. This law can be demonstrated with slightly longer calculations for ellipses.

Kepler's laws are verified in the movements of celestial bodies. They also govern the movements of bodies attracted by the Earth and, therefore, those of satellites and rockets. The figure opposite illustrates the various situations that can arise. In case 1, the velocity is insufficient and the body falls back to earth after describing a portion of an ellipse. Case 2 is that of a satellite in circular orbit, with a velocity of 7.93 kilometers per second. Case 3 is that of an elliptic orbit. The body breaks free from terrestrial attraction when the velocity reaches 11.2 kilometers per second (parabolic path indicated 4). When velocities are higher (5) the paths are hyperbolas.

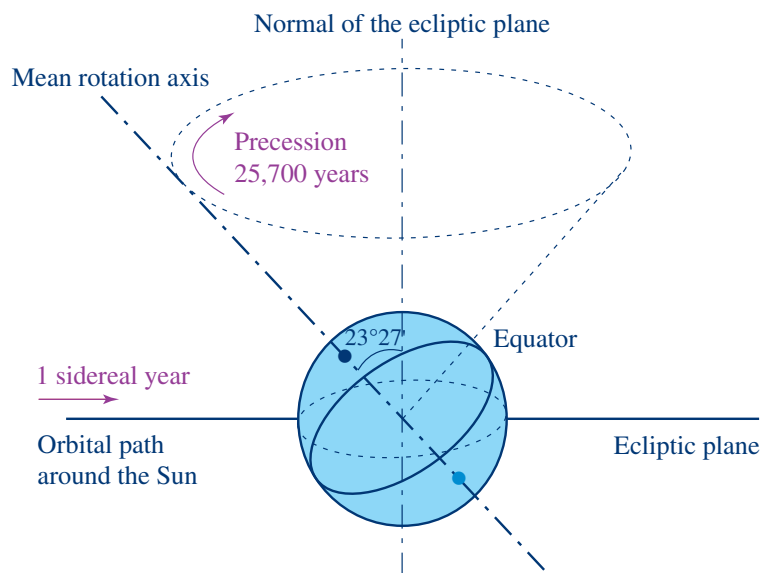


Appendix 13

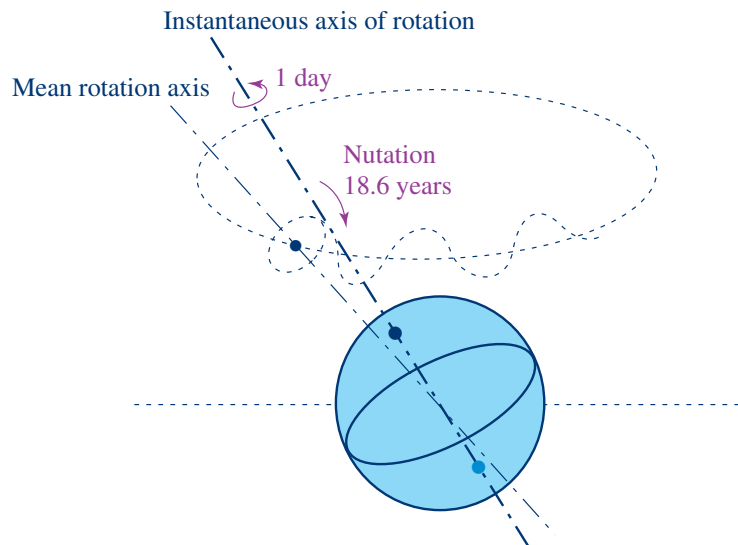
SIDEREAL TIME AND SOLAR TIME

The oscillations of the Earth as it rotates

The Earth rotates on its axis from west to east around the polar axis and it also rotates around the Sun from west to east in a plane called the ecliptic plane. Its North-South axis is inclined by $23^{\circ}27'$ on this plane. This angle between the North-South axis and the norm on the ecliptic plane remains the same through the course of time. However, the North-South axis describes a cone in 25,700 years, like the axis of rotation of a spinning-top. This cone is described from East to West, unlike the previous rotations. This retrogradation is called the precession of the equinoxes. It is due to the fact that the Earth is not perfectly spherical and homogenous but has a bulge on the equator. The action it undergoes due to the Sun, the Moon and even the other planets of the solar system tends to bring this bulge back into the ecliptic plane and generates the precession.



The Earth rotates around the Sun in one sidereal year, defining the ecliptic plane. The mean axis of rotation of the Earth forms an angle of $23^{\circ}37'$ with the ecliptic norm and describes a cone in 25,700 years.



The instantaneous axis of rotation of the Earth oscillates around the mean axis, describing a cone with a vertex angle of $18''4$ in 18.6 years. Obviously, the Earth rotates on its own instantaneous axis of rotation in one day.

A second perturbation superimposes itself on the precession of equinoxes: nutation. Of lesser span but with a far shorter period, 18.6 years, nutation is due to the variations in the orbital plane of the Moon. It adds a slight oscillation to the precession of the equinoxes as shown on the above figure. Finally, numerous terms of very low amplitude, of Moon-Sun origin, must be added to the principal term of nutation.

The duration of one year

Due to precession, the year is not identical for an observer placed outside the Sun-Earth system and for an observer on the surface of our planet. For the former, the time it takes for the center of the Earth to go back to the same point after one rotation around the Sun constitutes the sidereal year. This time is equal to 365.263 36042 days of 24 hours¹ (365 days 6 hours 9 minutes 9 seconds). The observer on the surface of the Earth defines his year, called the tropical year, as the time required to return to the same position in relation to the Sun. Since, meanwhile, the rotation axis, has precessed inversely to the direction of rotation of the Earth around the Sun, that year is slightly shorter than the sidereal year: 365.242 19879 days of 24 hours (365 days 5 hours and 48 minutes). The creation of the calendar led to the definition of the Julian year that fixed the duration of the year at 365 days, with an extra day every four years (leap years). The advance of about 21 minutes of the

¹ 1 hour = 3 600 seconds, the second being defined independently of the terrestrial rotation as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the cesium 132 atom.

tropical year on the sidereal year is at the origin of the introduction of the Gregorian calendar, which corrected the Julian calendar: the years that would normally be leap years but which cannot be divided by 400 remain normal: 2000 was a leap year whereas 1900 was not. The residual error is one day every 3000 years.

The duration of one day

The duration of the day is not the same for all the observers. The effect of precession alone cannot explain this difference. For an observer a long way off, the sidereal day is the mean interval of time between two consecutive transits of any star at its zenith above a point on Earth. For the observer on the surface of the Earth, the solar day is defined as the mean time gap between two successive transits of the Sun above the same longitude (of the meridian of a same point). During the time the Earth takes to rotate on its axis, it rotates slightly around the Sun, in the same direction. This explains why the solar day is 3 minutes and 56 seconds longer than the sidereal day; the former lasts 24 hours and the second 23 hours 56 minutes and 4.0905 seconds.

The values fluctuate for various reasons. Let us mention the frictional effect of tides (the influence of the Moon and of the Sun) that slows down of the rotation of the Earth around its axis and, consequently, an increase in the duration of a day amounting to 0.00164 second per century: the last dinosaurs lived in days a quarter of an hour shorter than ours. However, this value giving the slowing-down rate per century is not constant: it varies as a function of the movement of masses inside the Earth (see chapter 2) that can both slow down and accelerate the rotation, and also in function of the gravitational influence of other bodies. This slowing down has a considerable effect on the link between the Earth and the Moon. Due to the law of conservation of the kinetic moment, the Moon moves further away by a few centimeters every year.

We must therefore beware of the definition of years and days that we use.

Appendix 14

THE CHARACTERIZATION OF MAGNETIC ACTIVITY BY MEANS OF INDEXES

We have examined a great many magnetospheric phenomena, all more or less connected to the existence of the terrestrial magnetic field. Their complexity immediately raises the question of the measurement of their evolution. How is it possible to record magnetic perturbations in such a way that their major characteristics can be perceived rapidly? This problem is identical with that of the identification of solar activity and requires an indicator: the index of magnetic activity.

The geomagnetic field is the resultant of the intrinsic field of the Earth with its specific variations and the perturbations due to interactions with the solar wind and to ionospheric currents. These interactions vary according to the latitude from which they are observed: the polar cap is governed by the open field lines, auroral ovals by closed lines in the magnetosphere, low latitudes by the ring current. The intermediate zones are sensitive to all the phenomena at one and the same time.

The idea of defining a global index dates back to 1939, that is, before the digital era. Therefore the first, called "K", is very inaccurate. However, with a view to establishing a data base permitting the long term study of variations of the field, it is still calculated. It describes the magnetic activity every 3 hours. The horizontal components of the magnetic field are measured then the variation that is known to be due to terrestrial, global or local occurrences is subtracted (what is known as the S_R system for Solar Regular conditions, whose average defines a system called S_q for Solar Quiet conditions). There are 13 observatories, of which only two are in the southern hemisphere. There are none in Africa, South America, Asia or Eastern Europe. Not one of them is located in a sea or an ocean. In each observatory, the magnetic field is averaged over three hours and adjusted to a quasi logarithmic scale K that ranges from 0 (no activity) to 9 (very active conditions). This index is, therefore, a code and letters could have been used instead of numerals.

These K indexes are then averaged, applying a coefficient that takes into account at one and the same time the poor repartition of the measuring stations and the fact that magnetic excursions are more considerable at high latitudes than at low

latitudes. This average gives a planetary index Kp. To fine it down a little, it is allowed 28 values comprised between 0 and 9 with three possibilities for an intermediate number (for instance 5–, 5, 5+).

The increasing number of measurement stations has allowed the emergence of indexes calculated in the same way as K but with better latitude distribution and adapted to the northern (index n) and southern (index s) hemispheres. However, since no arithmetic calculation is possible with scale K, in 1951 a linear index was defined. This is called equivalent planetary amplitude and written Ap. The daily mean value of Ap (over 8 values each representing 3 hours' data) gives a daily Ap index in magnetic unit 2 nT (n corresponds to 10⁹ Tesla). Since the regular tendency to variations of the field has been dropped, index Ap represents only the perturbation of the magnetic field.

Indexes Kp and Ap are remarkably accurate for the description of global ionospheric phenomena. However, at high latitudes, the magnetic behavior becomes very specific. Index AE has been devised for auroral zones; the measurement stations are located between the geomagnetic latitudes of $\pm 60^\circ$ and $\pm 71^\circ$. In the same way, the equatorial regions are affected by the ring current whose perturbations depend neither on the local time nor on the longitude. A network of five observatories located around the equator provides the Dst index for these zones.

Modelization of the terrestrial environment is based on these indexes that have to be predicted or estimated according to the specific requirements.

Appendix 15

THE VARIATION IN MOLECULAR CONCENTRATION WITH ALTITUDE

Molecular concentration and pressure vary with the altitude according to relations that depend on thermodynamic conditions.

Let us consider the terrestrial atmosphere at an altitude z of between 10 and 30 kilometers in relation to the ground of the earth. This part of the atmosphere can be considered as isothermal, with a temperature T equal to 217 Kelvin on average. We shall neglect the variation of g , which is the acceleration of gravity with altitude, and consider the gas to be ideal. In these conditions, only the potential energy w of a molecule changes: $w = mgz$, m being the mass of a molecule. Using Boltzmann's statistic it is possible to know the number of molecules of various energies and, therefore, various altitudes:

$$N(z_1) = N_0 e^{-\left(\frac{w_1}{kT}\right)} = N_0 e^{-\left(\frac{mgz_1}{kT}\right)}$$

$$N(z) = N_0 e^{-\left(\frac{mgz}{kT}\right)}$$

whence
$$N(z) = N(z_1) e^{-\left(\frac{mg(z-z_1)}{kT}\right)}$$

By introducing the molar mass M , the Avogadro number $\mathcal{N}$ ($m = \frac{M}{\mathcal{N}}$) and the constant of ideal gases R ($k = \frac{R}{\mathcal{N}}$) we can write the molecular concentration $n(z)$ at altitude z :

$$n(z) = \frac{N(z)}{\text{Volume}} = n(z_1) e^{-\left(\frac{z-z_1}{H}\right)} \quad (1)$$

Where $H = \frac{RT}{Mg}$, called scale height, depends on the gas.

Since the gas is considered to be ideal, we can obtain the pressure $p(z)$:

$$n(z) = \frac{(p(z) V / RT)}{V} \mathcal{N} = \frac{p(z)}{kT}$$

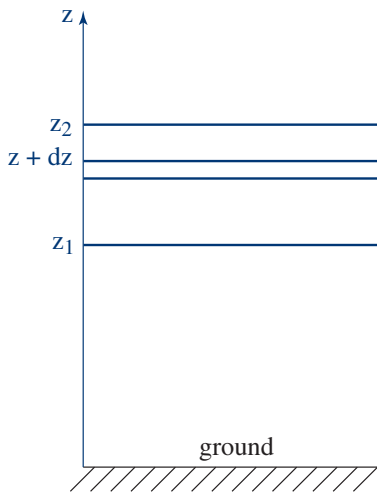
and

$$p(z) = p(z_1) e^{-\left(\frac{z-z_1}{H}\right)} \quad (2)$$

This relation remains valid if we consider a blend of gases with a partial pressure $p_a(z)$ for each gas:

$$p_a(z) = p_a(z_1) e^{-\left(\frac{z-z_1}{H_a}\right)}$$

where H_a is the scale height equal to $\frac{RT}{M_a g}$ and M_a is the molar mass of the gaseous component under consideration.



We could also have obtained the law of variation of the pressure by writing the difference in pressure between two separate points of dz :

$$dp = -\rho g dz$$

(where ρ is the mass per unit volume equal to $\frac{M}{V}$)

$$\frac{dp}{p} = -\frac{M}{RT} g dz \quad (3)$$

or by integrating between z_1 and z :

$$p(z) = p(z_1) e^{-\left(\frac{z-z_1}{H}\right)}$$

Using relation (3) we can find relation (2) concerning the variation of the pressure with altitude in the stratosphere. Comparable

calculations can be performed in non-isothermal conditions. For instance, at low altitudes ($0 < z < 2$ kilometers) where the temperature obeys a hyperbolic law:

$$T(z) = \frac{T_0}{1 + az}$$

By replacing $T(z)$ in relation (3) and integrating, we obtain for $p(z)$:

$$p(z) = p(0) e^{-\left(\frac{Mg}{RT_0} z \left(1 + \frac{a}{2} z\right)\right)}$$

In the text we also find a mention of the case of the linear decrease in temperature with altitude. This is what occurs between 2 kilometers and 9 kilometers. If T_1 and z_1 are the temperature and the altitude at 2 kilometers, we can write:

$$T(z) = T_1 (1 - bz)$$

By replacing $T(z)$ once again in (3) and integrating, we obtain:

$$p(z) = p(z_1) \left(\frac{1 - bz}{1 - bz_1} \right)^{\frac{Mg}{bRT_1}}$$

that corresponds to a continuous variation of p with altitude z .

Appendix 16

ELEMENTS OF ATMOSPHERIC CHEMISTRY

In the atmosphere, particles can interact with the solar photons or with each other. In the first case, we talk about photochemistry, whereas the second case relates to classic chemistry.

Photochemistry

There are three ways in which a constituent M of the atmosphere can absorb a photon: excitation, molecular dissociation and ionization.

Excitation by absorption of a photon of frequency ν is written:



M represents an atmospheric atom or molecule and M^* an excited atom or molecule, i.e. one whose energy is higher than that of the stable atom. In equations pertaining to radiation-matter interaction, a photon is traditionally noted by its energy $h\nu$ where h represents Planck's constant. The minimum energy (or maximum wavelength) required for radiation-matter interaction to take place is called a threshold. The excitation thresholds in the terrestrial thermosphere are sufficiently low for the whole of the ultraviolet radiation to have the power to excite. There are different kinds of states of excitation. An electronic excitation corresponds to the absorption of the energy of the photon by an electron. The electron then moves away from the atomic nucleus. A vibratory excitation corresponds to a molecule being made to vibrate at characteristic frequencies of 100 billion movements per second in the thermosphere. A rotational excitation makes a molecule rotate on its axis, typically 10 billion times per second in the thermosphere.

A photon can also **dissociate** a molecule, i.e. break it up into several atoms or molecules. In the thermosphere, the only existing molecules are N_2 , O_2 and H_2 , made up of two identical atoms. Among these, the highest threshold of photodissociation in terms of wavelength (and therefore the lowest in frequency) is found for O_2 :



The symbol of the state of excitation of the atom is in brackets. State (³P) of atomic oxygen is the fundamental state and this reaction can take place for wavelengths lower than the threshold $\lambda = 242.4$ nanometers. Naturally, at least one of the atoms formed by photodissociation can be in an excited state, state (¹D) of atomic oxygen, for instance:



This state is de-energized toward state (³P) and emits a red light as mentioned in chapter 2 (illustrated by figure 2.14).

A photon can also tear an electron away from the target molecule or atom. Once again, the highest **ionization** threshold in terms of wavelength of the thermospheric elements is that of the oxygen molecule:



When the ionizing radiation has a wavelength of less than 73.2 nanometers, the molecular oxygen ion can also be in an excited state.

Let us consider that p is indifferently the process by which a particle absorbs a photon. This can be excitation, dissociation or ionization. The photon flux that reaches altitude z of the atmosphere and wavelength λ is $I(\lambda, z)$. Its units are $\text{m}^{-2} \text{s}^{-1} \text{nm}^{-1}$: it is a photon flux for a clearly defined wavelength. The probability that a photon will be absorbed by target particle M via process p can be quantified by using the "cross-section" σ_M^p concept, the unit of which is the square meter. The cross-section varies in function of the wavelength. The cross-section can be pictured as the equivalent surface on which interaction can take place between two particles. At a given altitude z of the atmosphere, the production (in $\text{m}^{-3} \text{s}^{-1}$) of particles dissociated, excited or ionized by one of the processes p is proportional to this effective section, to concentration n_M of particles M at this altitude and to the flux $I(\lambda, z)$ of photons that arrive in z at effective wavelengths for p at noon at the equator:

$$\text{Prod}_M^p(z) = \int n_M(z) \sigma_M^p(\lambda) I(\lambda, z) d\lambda$$

At other solar angles, a projection on the altitude axis is necessary. This formula permits some digital estimations: in the thermosphere, the cross-sections are roughly 10^{-21} square meters. Let us suppose that this value is constant for ionization. The solar flux integrated on all the wavelengths of the extreme ultraviolet is approximately 10^{14} photons per square meter and per second, arriving under normal incidence at 150 kilometers in an atmosphere with 2×10^{16} molecules per cubic meter (made up half and half of oxygen molecules and nitrogen molecules). Digital application leads to the production of 2×10^9 electrons per cubic meter and per second.

In a stationary state and for an altitude of between 80 and 200 kilometers, a simple law makes it possible to deduce the electron concentration $n_e(z)$ using an effective recombination coefficient α_{eff} :

$$n_e(z) = \sqrt{\frac{\text{Prod}_M^p(z)}{\alpha_{\text{eff}}}}$$

α_{eff} is approximately $3 \times 10^{-14} \text{ m}^3 \text{ s}^{-1}$ at 90 kilometers, $10^{-14} \text{ m}^3 \text{ s}^{-1}$ at 110 kilometers and $7 \times 10^{-15} \text{ m}^3 \text{ s}^{-1}$ at 200 kilometers. With a value of $8 \times 10^{-15} \text{ m}^3 \text{ s}^{-1}$ at 150 kilometers, we obtain a value of $5 \times 10^{10} \text{ m}^{-3}$ for electron concentration, which is an accurate value when the Sun is moderately active.

Atmospheric chemistry

Electrons, ions, atoms or molecules that are excited or have been created by the absorption of a solar photon play a part in various chemical processes with the ambient atmosphere. A chemical transformation is a reaction that puts two bodies into interaction. It can, therefore, be characterized by an effective section. However, when calculating reaction times it is often simpler to use a chemical coefficient, connected to the cross-section¹, that characterizes the velocity at which the reaction takes place. The most general form of a coefficient k of a chemical reaction is given by:

$$k = A T^B \exp\left(\frac{-C}{T}\right)$$

T is the temperature in Kelvin; A , B and C are specific constants of each chemical reaction. Modelization of the thermosphere is made more complex by the fact that coefficient k usually depends on the temperature. However, simplification is possible insofar as, at some time or another, chemical reactions involve only two bodies. Under certain circumstances, these reactions can be reduced to the effective recombination coefficient given above.

1 Given a cluster of particles with a distribution of velocities $f(v)$. By definition of the distribution function, the mean velocity of the particles is $\int f(v) v dv$. Given the example of a cluster of particles made up of solar wind ions with a mean velocity of 370 km s^{-1} and concentration n_i . It can be assumed that these ions collide with a population of low energy thermospheric particles M , of concentration n_M . This interaction is characterized by the effective section of interaction σ . It can also be characterized by reaction coefficient k according to: $k = n_M n_i \int \sigma f(v) v dv$. Since $f(v)$ is generally a function of the temperature of the medium, the reaction coefficient also usually depends on the temperature.

Appendix 17

THE MOVEMENT OF A CHARGED PARTICLE IN A MAGNETIC FIELD TUBE

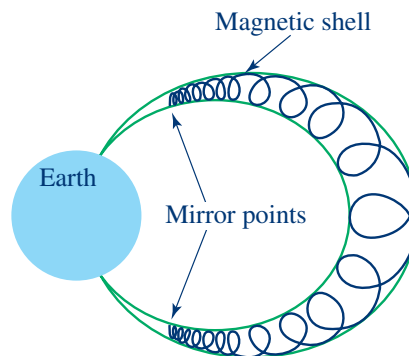
In appendix 9 we described the movement of a particle in a magnetic field and how the magnetic field and the particles can be linked, "frozen".

Let us consider a charged particle spiraling in increasingly narrow magnetic field lines. This is what occurs when particles near the surface of the Earth at a high latitude. This case is shown in the figure below.

As it moves, the particle sees the amplitude of the magnetic field vary and therefore its gyration radius changes throughout its path, as shown in the figure. The frequency of rotation, that is proportional to the magnetic field, increases as it moves down toward the Earth. It can be demonstrated that during this movement, a quantity called the first adiabatic invariant is conserved. It is expressed:

$$\mu = \frac{mv_{\perp}^2}{2B}$$

$v_{\perp}$ refers to the velocity perpendicular to the magnetic field, m to the mass, B to the intensity of the magnetic field.



A charged particle in a magnetic field spirals along a field line. When the lines narrow, as they do when nearing the Earth, the diameter of the spiral becomes smaller and the particle revolves increasingly fast. At the same time, however, the velocity at which it moves down decreases until it cancels itself out. The particle then sets off again in the opposite direction: this is the magnetic mirror effect.

The energy of this increasingly fast movement perpendicular to the magnetic field is consumed to the detriment of the energy of the parallel movement. Total kinetic energy must be conserved; this is the sum $\frac{1}{2} m(v_{\perp}^2 + v_{\parallel}^2)$ where $v_{\parallel}$ is the velocity parallel to the magnetic field. If the perpendicular velocity increases, this conservation means that the parallel velocity has to decrease. Eventually, the particle can no longer move forward and can be forced to set off again in the opposite direction. This variation can make a particle "rebound", giving the impression that the field acts like a mirror. The reflection generally takes place at the two extremities of the field lines and its effect is to trap the particles in field tubes that form energized particle reservoirs. This rebound effect is called the **magnetic mirror**. The position of the rebound, or mirror, point in relation to the atmosphere conditions a large part of the physics of the magnetosphere and the ionosphere. For one thing, it depends on the angle at which the particle hits the atmosphere (in relation to the magnetic field): the smaller the angle, the lower it is. The lowest altitude is reached by a particle traveling parallel to the field, with no perpendicular velocity. This leading angle varies throughout the life of the particle, due to collisions with other particles.

Particle movements can become more complicated if another force $\vec{F}$ superimposes itself on the Lorentz force due to the magnetic field. The particle carries on spiraling but that of the center guide is governed by this force, as is the direction in which the spiral is described by the particle. To study the movement of the center guide, we can consider that its velocity is constant and its acceleration therefore equal to zero and write, using the fundamental equation of dynamics:

$$\vec{0} = \vec{F} + q \vec{v} \wedge \vec{B}$$

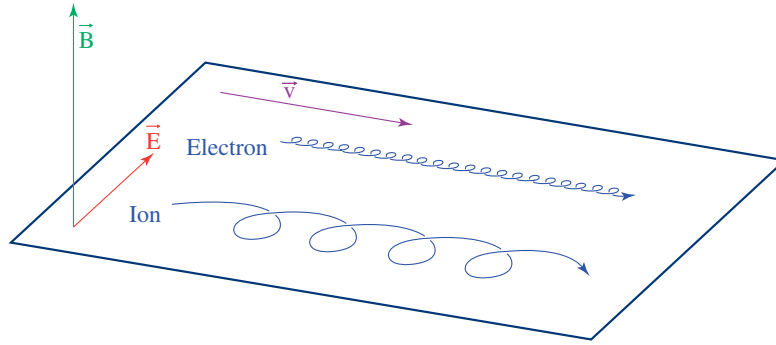
whence

$$\vec{F} = -q \vec{v} \wedge \vec{B}$$

If we multiply vectorially by $\vec{B}$ to the left and the right, we easily obtain:

$$\vec{v} = \frac{\vec{F} \wedge \vec{B}}{q B^2}$$

If the force derives from an electric field, it is written $\vec{F} = q\vec{E}$. In the stationary equation of particle velocity, the charge is simplified: the ions and the electrons drift in the same direction. However, they wind round the direction of the magnetic field in a different direction (figure 2). This case can be encountered in the terrestrial magnetosphere: the ions and electrons trapped on the night side are all forced to move toward the front of the magnetosphere.



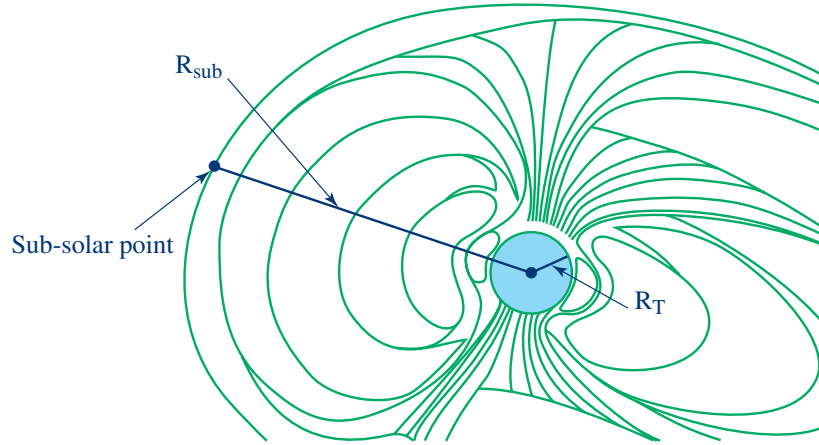
However, in a field of gravity, the force is written $\vec{F} = m \vec{g}$. The result is that the velocity of the center guide depends at one and the same time on the mass and the charge sign of the particle: a current is created. This is particularly important for massive planets, such as Jupiter.

Another interesting case corresponds to the existence of a distinctive magnetic field gradient. The effect of this gradient can then be compared to a force $\vec{F} = -\mu \vec{\nabla} \vec{B}$, where μ represents the first adiabatic invariant. The derivation velocity obtained decreases according to the square of the intensity of the magnetic field and depends on the sign of the charge. This case can be encountered in the terrestrial magnetosphere when the particles come back from the night side toward the day side of the Earth: the closer they are to the Earth, the higher the intensity of the field. Added to the spiraling movement we have a separation of charges in a direction perpendicular to both the field and the gradient, triggering the ring current mentioned in chapter 2.

Appendix 18

THE CALCULATION OF THE POSITION OF THE MAGNETOPAUSE

The position of the magnetopause is determined by the equilibrium between the kinetic pressure of the solar wind and the magnetic pressure of the terrestrial field. Let us calculate the position of the magnetopause on the Earth-Sun axis. This point is called the sub-solar point. The figure below recalls the shape of the magnetosphere and shows where the following calculation applies.



The kinetic pressure of the solar wind is written (see appendix 10):

$$p_{\text{sw}} = n_{\text{sw}} k_B T_{\text{sw}}$$

k_B is the Boltzmann constant. The sw indexes mean "solar wind" and T_{sw} is the mean temperature of the solar wind. In the kinetic pressure exercised by the solar wind, the electrons, that are 1836 times lighter than the protons, are neglected and only the protons are conserved. Therefore, n_{sw} represents the ion concentration of the solar wind ($5 \times 10^6 \text{ m}^{-3}$ on average). Assuming they travel at a velocity v_{sw} ($370 \times 10^3 \text{ m s}^{-1}$), their kinetic energy can be expressed as a function of the mean quadratic velocity:

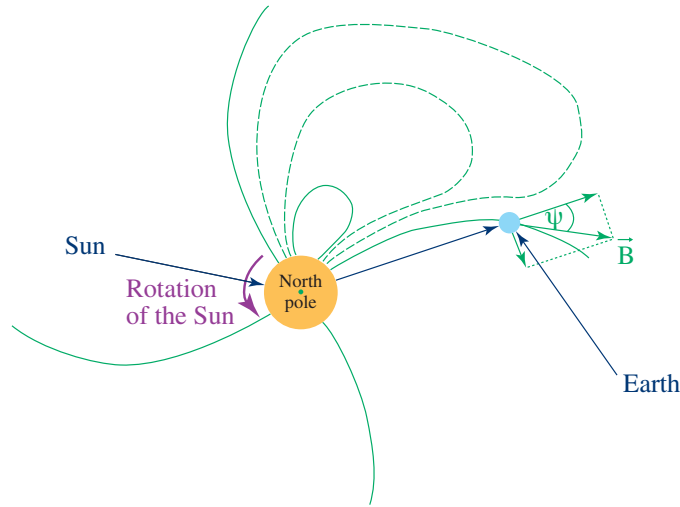
$$E = \frac{1}{2} m_{\text{sw}} \overline{v_{\text{sw}}^2}$$

Since the energy of the particles frozen in the interplanetary magnetic field is $E = k_B T_{sw}$ the pressure of the solar wind is written:

$$p_{sw} = \frac{1}{2} n_{sw} m_{sw} \overline{v_{sw}^2}$$

If we take into account the Archimedes' spiral (see chapter 1), i.e. the angle θ between the solar wind and the Earth-Sun axis, p_c becomes:

$$p_{sw} = \frac{1}{2} \cos^2 \theta n_{sw} m_{sw} \overline{v_{sw}^2}$$



As introduced in appendix 10, the magnetic pressure is written:

$$p_{magn} = \frac{1}{\mu_0} \frac{B^2}{2}$$

If we retain for field B the dipolar variation described in appendix 4, at a point R (expressed in terrestrial radii), knowing the value B_T of the field at surface R_T (approximately 5×10^{-5} T), we obtain the relation: $BR^3 = B_T R_T^3$. The magnetic pressure then becomes:

$$p_{magn} = \frac{1}{2\mu_0} B_T^2 \frac{R_T^6}{R^6}$$

Distance R_{sub} between the center of the Earth and the sub-solar point, where the wind is stopped by the field, is given by the equality $p_{sw} = p_{magn}$. We can deduce:

$$R_{sub} = \left[\frac{B_T^2}{\mu_0 \cos^2 \theta n_{sw} m_{sw} \overline{v_{sw}^2}} \right]^{\frac{1}{6}} R_T$$

With the numerical values given previously and for an angle θ of 62.6° , this calculation gives a distance of approximately 12.5 terrestrial radii. This is the mean position of the sub-solar point.

Appendix 19

THE PLANETS OF THE SOLAR SYSTEM IN THE GLARE OF THE SUN

Chapter 2 gave us some characteristic data concerning the planets of the solar system. Chapter 3 then showed how solar activity affects our geophysical environment. The question of the interactivity between the Sun and the magnetized environments of the other planets only arose recently and led us to view the planets in a completely different light. Apart from the purely geophysical interest, it furthered our knowledge of our own environment and its future development.

The following table presents a few characteristic data concerning the magnetized planets of the solar system

Parameters of planets of the solar system in connection to space weather

	Period of rotation (hours)	Magnetic moment compared with that of the Earth	Magnetic field on the equator [10^{-4} T]	Angle between the dipole axis and the axis of rotation	Mean solar wind concentration (e^-+p^+)[cm^{-3}]	Theoretical* distance of the sub-solar point of the magnetosphere**	Real*** distance of the sub-solar point of the magnetosphere**
Mercury	1404	4×10^{-4}	2×10^{-3}	?	45-100	1.3 R_M	1.6 R_M
Earth	24	1	0.31	11.3°	10	12.5 R_T	11 R_T
Jupiter	9.9	20	4.28	-9.6°	0.4	30 R_J	50-100 R_J
Saturn	10.7	600	0.22	0°	0.1	14 R_S	16-22 R_S
Uranus	7.2	50	0.23	-59°	0.03	18 R_U	18 R_U
Neptune	16.1	25	0.14	-47°	0.005	18 R_N	23-16 R_N

* calculated using the formula in appendix 18.

** expressed in planetary radius.

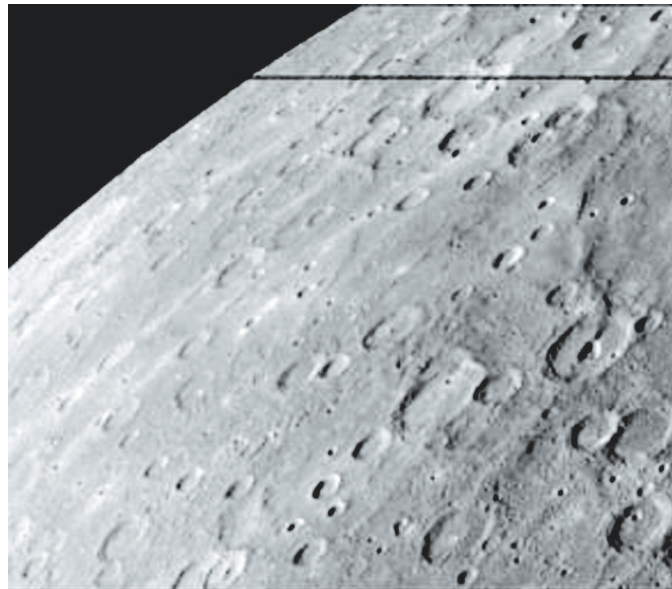
*** takes into account the Archimedes spiral and a coefficient of porosity of the magnetosphere that has not been mentioned here.

What we see immediately is that Venus and Mars are not in the list since they do not have (or no longer have) a magnetic field. The most impressive field is that of Jupiter, nearly 14 times more intense than that of the Earth. The Earth and the other

giant planets are very comparable from a magnetic point of view, in spite of the widely different planetary dimensions that reveal considerable differences in their internal structures.

Let us run through these planets from the point of view of their situation in the glare of the Sun.

Mercury, at 0.357 AU from the Sun, has a tenuous atmosphere. Its density can be compared to that of the Earth but its size reminds us more of that of the Moon. The major impact of the solar wind was to blow away the primordial atmosphere of Mercury; this was a devastating effect of local space weather. At the present time, its atmospheric pressure is 100 billion times lower than that of the Earth.

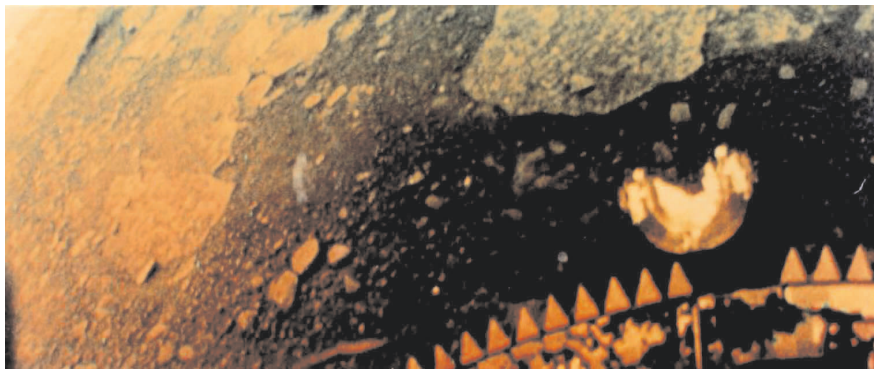


Mercury, photographed from the American space capsule Mariner 10 as it flew over (credit NASA/JPL/Northwestern University).

The few particles of gas present in the diffuse atmosphere of Mercury are Helium, traces of Argon, Sodium and Neon. Furthermore, this planet has a dipolar magnetic field of low intensity. Certain particles of solar wind make the same journey around it as the one described in chapter 2 in the case of the Earth, the difference being that there is not enough gas to slow them down. Therefore, the particles crash to the ground on Mercury. If this reaction was electroluminescent, the aurora on Mercury would be a rocky one! During strong solar eruptions, the situation is even more strange: the solar wind is so intense that it compresses the magnetic field of Mercury to such an extent that the sub-solar point (see appendix 18) of the magnetopause passes over to the night side of the planet, letting the solar electrons and protons crash down directly to the ground. In spite of its nearness to the Earth, very little is

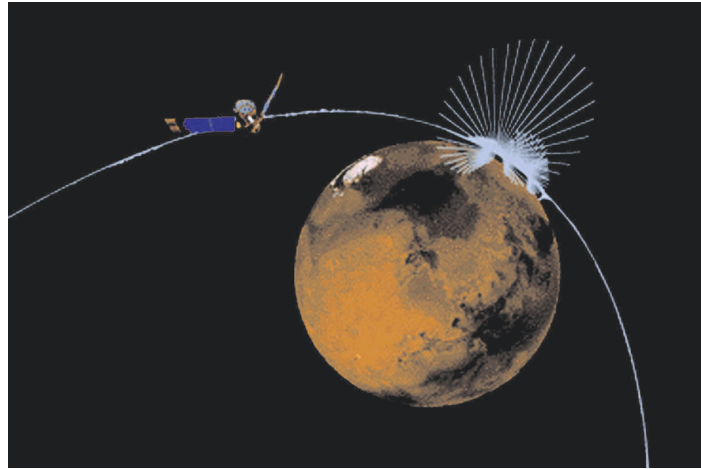
known about Mercury. This is due to its low distance in relation to the Sun, that makes an approach from space difficult. However, things may soon change since the European Space Agency has made this planet a priority for future missions.

Venus has a surprise in store: it has no significant magnetic field and, therefore, no magnetosphere. However, it has a dense atmosphere, 96% of which is CO. Since this molecule can be ionized by the solar radiation of the extreme ultraviolet, there is a diurnal ionosphere. The solar wind is unable to penetrate into the atmosphere of Venus because the ionosphere itself acts as a shield. The few electrons of the solar wind that manage to cross this barrier create a slight excitation: the auroral oval is simply a diurnal crescent, as observed by the ultraviolet spectrometer of the American satellite Orbiter.



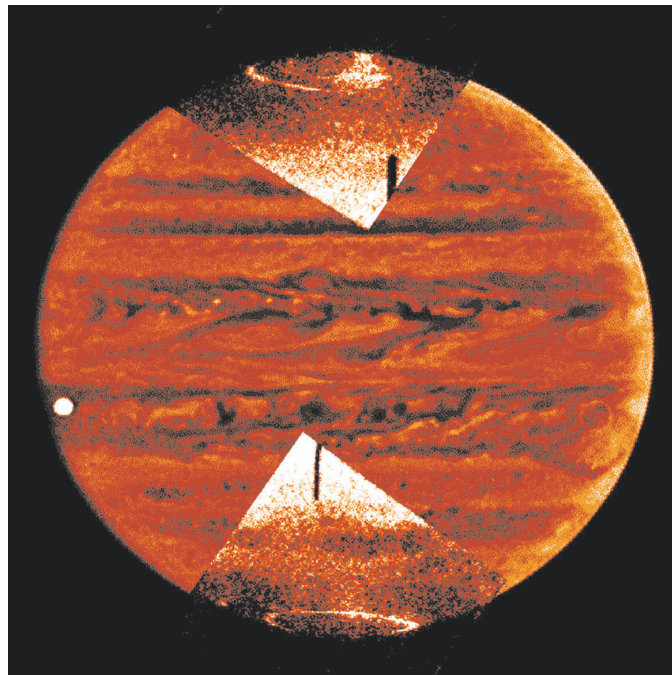
On March 1st 1982, the Russian station Venera 13 landed on the surface of Venus, at a latitude of 7.5° south and a longitude of 303° east. Venera carried a color camera that worked for 2 hours and 7 minutes before dying away. It obtained 14 pictures of the surface of the planet. At the bottom, we can make out part of the space probe.

Mars has always fascinated astronomers. Its atmosphere is composed of 95% CO₂. Its atmospheric pressure is one hundred to five hundred times lower than that of the Earth. In 1997, the Mars Global Surveyor probe showed that Mars once had a magnetic field; local reminiscences, retained in the ferromagnetic rock, were measured. This field has died away. Moreover, the atmosphere of Mars becomes ionized and the ions can be carried away by the solar wind. The atmosphere of the planet may have partially emptied in this way over thousands of years; if so, this would be one of the spectacular effects of space weather and could enable us in turn to predict the future of the terrestrial ionosphere. Future space experiments will tell us more.



Mars, when the Mars Global Surveyor probe flew over in 1998. This probe proved the existence of a residual magnetic field on the surface of the planet. This field, which is local, is shown in blue in the picture (credit NASA).

Jupiter has a magnetic field in its own image: ten times more intense than the terrestrial field. The considerable gravity of the planet enabled it to retain the atmosphere of



This assembly (in false colors) shows the southern and northern auroral ovals of Jupiter, photographed in the ultraviolet and superposed on a photograph taken in the visible. The white spot on the left is the satellite Io in transit (credit FOC-HST; L. Pallier and R. Prangé, IAS Paris).

primordial gas of the solar system, consisting primarily of hydrogen and helium¹. The auroral ovals of Jupiter have been observed by several instruments, including the ESA's Faint Object Camera on board the NASA space telescope. Unfortunately, they are not visible to the eye since they emit in the ultraviolet. In the photo-assembly of the previous figure, they have been superimposed on a photograph taken in the visible range at the same instant.

A specificity of Jupiter's ionosphere is due to the presence of Io, a volcanic satellite that blows sulfur dioxide out into space. This gas is also ionized by the solar ultraviolet, leaving a magnetic core of conductive plasma. The ionized particles are trapped by Jupiter's magnetic field and forced to follow it until they fall into its atmosphere. Then, like the particles of the solar wind, they excite and ionize the gas they encounter, that returns to equilibrium, emitting light in particular. It is this trail, that of Io, that is easily recognized in the figure, equatorward to the oval itself. Furthermore, measurements taken by the American probe Galileo seem to show that Io has its own magnetic field, as does Ganymede, another of Jupiter's satellites. The magnetic field of the latter is without ambiguity since it is five times more intense than the mean local field of Jupiter, hardly 500 times lower than that of the Earth. It was discovered on December 7th 1996 and the results were very soon published in the magazine *Nature*. The enormous interest of this discovery is due to the fact that since their mass is so low, nobody had ever imagined that Jovian satellites could have the metallic nucleus necessary for the presence of a magnetic field.

When approaching Europa, the magnetometers also measured an increase in the local magnetic field, although it was very weak, 5000 times lower than that of the Earth. Near Callisto, a field five times weaker still was measured.

These discoveries already have their legend. When Galileo took off, it was found that its main antenna had not deployed correctly. All that remained to transmit data was the emergency antenna. While the satellite was heading for its destination, the engineers worked relentlessly, compressing the data to be sent. However, it was no longer possible to run all the experiments taken on board at the same time: all the data could not be transmitted. It was therefore decided to switch off the magnetometer as it neared the Jovian satellites, so sure was everybody that they could not have a magnetic field. Legend has it that an operator forgot to switch off the instrument as it flew over Io (obviously, this is done by remote control).

1 The atmospheres of Mars, Venus and in the Earth stemmed from complex phenomena following the forming of these planets. The atmospheres of giant planets (Jupiter, Saturn, Uranus and Neptune) were already present during their forming.

Discovery of Ganymede's magnetic field by the Galileo spacecraft

M. G. Kivelson*†, K. K. Khurana*, C. T. Russell*†,
R. J. Walker*, J. Warnecke*, F. V. Coroniti‡,
C. Polanskey§, D. J. Southwood*|| & G. Schubert*†

* Institute of Geophysics and Planetary Physics, † Department of Earth and Space Sciences, ‡ Department of Physics, University of California, Los Angeles, California 90095-1567, USA

§ Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109, USA

|| Department of Physics, Imperial College of Science, Technology, and Medicine, London SW7 2BZ, UK

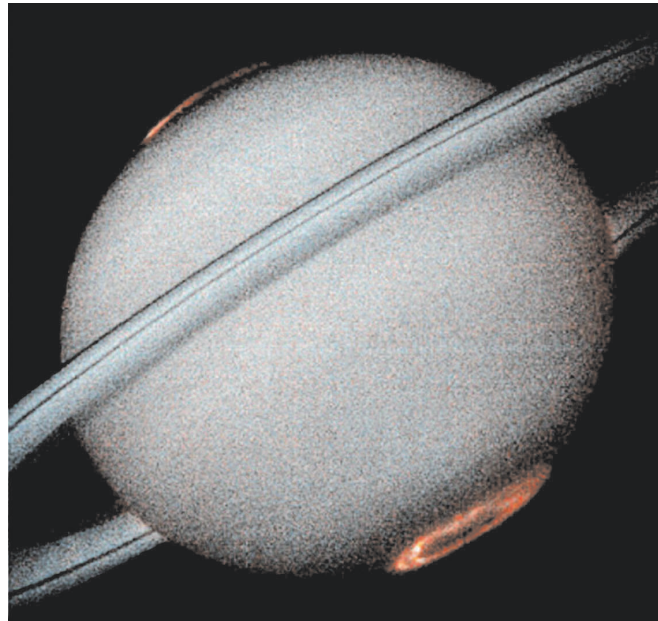
THE Galileo spacecraft has now passed close to Jupiter's largest moon—Ganymede—on two occasions, the first at an altitude of 838 km, and the second at an altitude of just 264 km. Here we report the discovery during these encounters of an internal magnetic field associated with Ganymede (the only other solid bodies in the Solar System known to have magnetic fields are Mercury, Earth and probably Io¹). The data are consistent with a Ganymede-centred magnetic dipole tilted by $\sim 10^\circ$ relative to the spin axis, and an equatorial surface-field strength of ~ 750 nT. The magnetic field is strong enough to carve out a magnetosphere with clearly defined boundaries within Jupiter's magnetosphere. Although the observations require an internal field, they do not indicate its source. But the existence of an internal magnetic field should in itself help constrain models of Ganymede's interior.

On Galileo's first inbound pass following orbital insertion, the magnetometer² measurements followed reasonably closely the predictions from a recent model of the magnetic field of Jupiter's magnetosphere³ that we refer to as the KK96 model. (This model consists of the O6 model⁴ of Jupiter's internal field plus the field of a warped and hinged current sheet parametrized to fit the magnetic field measured on the Pioneer 10 outbound pass near the dawn meridian.) The field increased in magnitude with approach to Jupiter and varied in orientation at Jupiter's rotation period. Data from 00:00 UT (universal time; h:min) to 12:00 UT on

537

On December 12th 1996, the magazine Nature published the discovery of Ganymede's magnetic field. As specified by M. Kivelson and his co-authors, at the time Io's magnetic field was purely hypothetical (reproduced by authorization of the magazine Nature, copyright 1996, Macmillan magazines Ltd).

Saturn also has both a magnetic field and an atmosphere whose composition is close to that of Jupiter. The axis of its magnetic field is almost the same as the geographical axis, which is an isolated case in the solar system. Its auroral oval was first observed in 1995 by the European Space Agency's Faint Object Camera on board the Hubble space telescope.



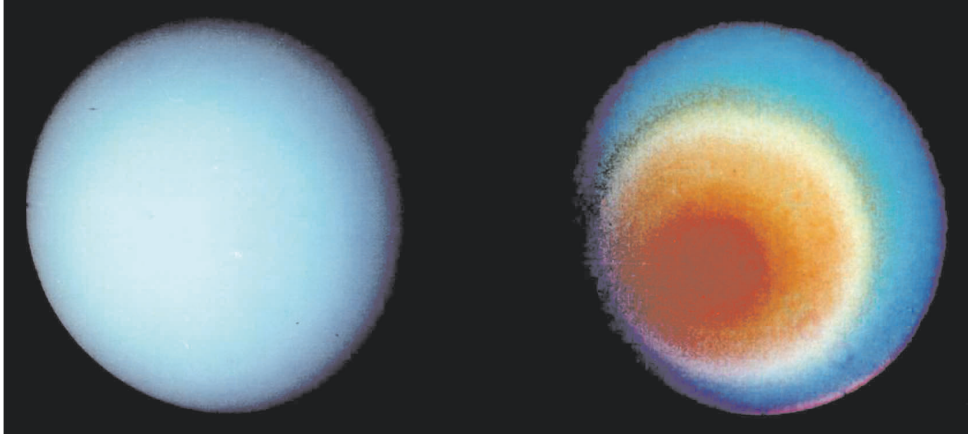
A picture that is no less spectacular showing the southern and northern auroral ovals of Saturn, photographed by the Hubble space telescope (credit STIS-NASA).

The study of Saturn is complicated by the presence of its rings but also and especially by that of Titan. Titan is a satellite with its own atmosphere but no known magnetic field². The particularity of its atmosphere is that its composition closely resembles that of the Earth. The composition of the terrestrial atmosphere is approximately two thirds molecular nitrogen to one third oxygen. On Titan, the ratio is two thirds molecular nitrogen to one third methane. This analogy opens up new horizons: could Titan provide us with data on prebiotic conditions i.e. those that prevailed before the emergence of life on the Earth? Titan has an atmosphere and also an ionosphere. This giant planet and its mysterious satellite will be explored by the ESA and NASA Cassini Huygens project during the first years of the twenty-first century.

Uranus is perhaps even more surprising: its geographical north pole points toward the Sun, but the magnetic pole is directed almost like that of the Earth. Until it was measured by Voyager, general comprehension of a planetary magnetic field

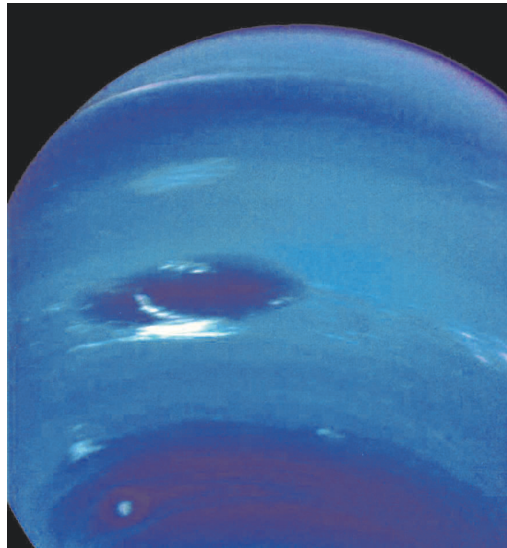
2 Since Galileo, cautiousness commands to avoid predictions on that burning issue.

stipulated that its axis should be roughly aligned on that of the rotation of the planet and nobody had even considered this difference of 55° . The Voyager satellite also detected a nocturnal aurora on Uranus, near to its magnetic pole.



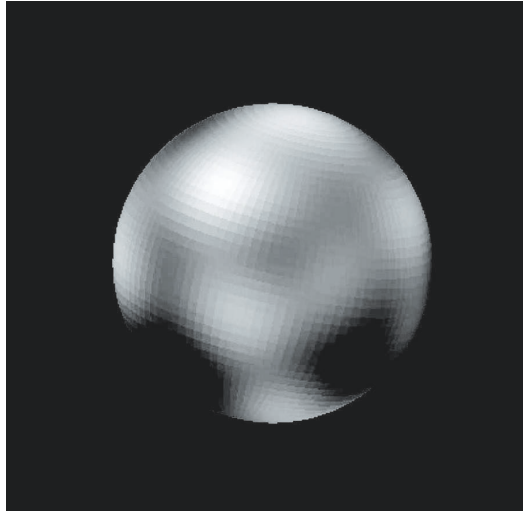
On the left, Uranus as it appeared to the American probe Voyager 2 on January 17th 1986, at a distance of 9.1 million kilometers. On the right, color coding shows up the auroral oval of the planet (credit NASA/JPL).

Neptune is the next to amaze us. The angle of inclination of the axis of rotation on the ecliptic is 29° , with a magnetic axis 45° from its geographical axis. The solar wind therefore enters directly into the polar cap. It also has an atmosphere. That is just about the extent of our knowledge...



On August 21st 1989, Voyager 2 passed Neptune and photographed its atmosphere from only 6.1 million kilometers, showing up the large dark spot, a cyclone and winds of more than 600 kilometers per hour (credit NASA/JPL).

Pluto: ... and it is a great deal compared with Pluto, whose polar auroras we know nothing about. We can be pretty sure that the extrasolar planets we are starting to discover will have other surprises in store for us!



Prior to this composite picture (June/July 1994) taken by the ESA's wide angle camera on board the Hubble space telescope, the surface of Pluto had never been photographed. Such contrasts were unexpected, revealing a complex object, not unlike the Earth (credit A. Stern – Southwest Research Institute; M. Buie – Lowell Observatory; NASA and ESA).

Appendix 20

THE MOON IN THE GLARE OF THE SUN

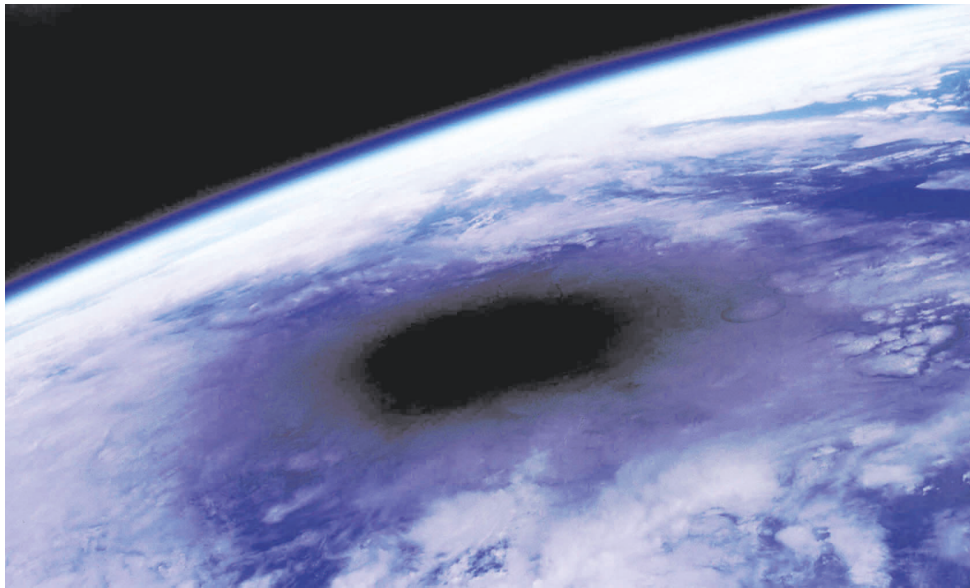
Although the presence of the Moon is only anecdotal as far as space weather is concerned, it is significant enough to be mentioned. Here we are not going to study the Moon in detail, we shall simply give a few elements concerning its relationship with the Sun.



The Moon rising above the atmosphere of the Earth (credit J.P. Haigneré, CNES).

The distance between the Earth and the Moon is 384,400 kilometers, i.e. a little more than 60 terrestrial radii. This means that, unlike Jupiter's satellites, the Moon is not protected by the terrestrial magnetosphere but is directly exposed to the solar wind. An interesting feature of the solar system is that the distance between the Earth and the Moon is 400 times less than the distance between the Earth and the Sun. The proportions are the same as the relationship between the diameter of the Moon (3,476 kilometers) and that of the Sun (1,392,000 kilometers), so that, seen from Earth, the satellite and the star seem to be the same size. This coincidence enables us to admire total eclipses of the Sun, like the one on August 11th 1999, that was visible from the north of France.

These proportions of 400 should not surprise us unduly, since they are purely conjunctural. The Moon moves away from the Earth by about 4 meters per century (see appendix 13); our remote descendants will no longer be able to see a total eclipse, since the Moon will appear increasingly small. As for the animals that lived 650 million years ago, they were certainly unable to admire an annular eclipse, since at that time the distance between the Earth and the Moon was approximately 58.4 terrestrial radii, compared with 60.4 at the present time. This ratio of 400 is, therefore, transitory as astronomical ages go. It is just by chance that we are here at the "right" time.



The Moon casting its shadow on the Earth during the eclipse on August 11th 1999. The picture was taken from the MIR space station, during the Perseus scientific and technological mission (credit J.P. Haigneré, CNES).

Finally, let us mention a recent discovery by the astronomer Jacques LASKAR, of the Department of Longitudes, in Paris. According to his models on celestial movement, the rotation axis of the Earth is not stable. Since there are more continents in the north of the planet than in the south, the difference in mass is enough to create a slight imbalance. If Jupiter passed behind the Sun, the rotation axis of the Earth would shift toward it under the combined effect of their gravities¹. Later, another configuration of the solar system could make the Earth lean to the

¹ We have already indicated that the force of gravitational attraction exerted on each other by two point masses m and m' or of spherical symmetry, separated by a distance d , is a force of intensity $F = G \frac{mm'}{d^2}$, where G is the universal constant of gravitation, equal to $6.672 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$.

other side. It would undoubtedly be very difficult, not to say impossible, to live on such a planet! According to J. LASKAR, it is the Moon that stabilizes the Earth. Ineluctably, as the distance between them increases, the stabilizing effect will disappear: this is one of the possibilities as to the end of our civilization.

Which of the phenomena of space weather affect the Moon? The solar wind and high energy cosmic radiation strike the Moon directly, as its orbit is outside the terrestrial magnetosphere. Since it does not have a protective atmosphere, it is also at the mercy of micro-meteorites and solar radiation. Under the influence of these aggressions, its surface is cracked, damaged and covered with dust that can be as fine as a few microns. In time, a layer 2 to 6 meters thick has formed; this is called a regolite. A "gardening" effect means that, like in the cultivated fields of our countryside, the stones from the subsoil can come to the surface. This internal movement of the regolite is approximately 1 meter per billion years.

Within the solar system, the regolite is a unique record of the history of the interplanetary medium; unlike on the Earth, no plate tectonics stir up the layers and make them disappear. Furthermore, by interpreting this record it is possible to distinguish between the sources that have an adverse effect on the surface since the higher we rise in latitude, the lesser the effects of the solar wind and radiation. The poles, in particular, are exposed only to cosmic radiation and micro-meteorites.

Appendix 21

COMETS, METEORS AND ASTEROIDS IN THE GLARE OF THE SUN

The Earth, the Moon (see appendix 21) and the planets (see appendix 19) are not the only bodies to be found in the solar system. Other celestial bodies circulate there: comets, meteors and asteroids.

Comets

Comets are small, icy bodies that travel within the solar system. They probably witness the formation of the solar system and constitute, on the border of the solar system—at between 20,000 and 50,000 AU¹—a tenuous sphere that bears the cloud name Oort. It was J.H. OORT who suggested its existence in the 1950s, on the basis of the analysis of the paths of approximately twenty comets. It is estimated that this cloud contains the nuclei of between 100 and 1000 billion comets. There is another comet source, in the shape of a flat ring extending from the orbits of Neptune and Pluto to the internal border of Oort's cloud: the Kuiper belt. It could contain more than tens times as many comet nuclei as Oort's cloud.

Comet nuclei are very irregular, "potato-shaped". They are made of ice, primarily water ice, with traces of ammoniac, methane, dicyanogen and carbon monoxide. They also contain minerals. Their diameter is very variable, from 1 to 100 kilometers, for a mass of between 10^{11} and 10^{13} kilograms.

They are exposed to gravitational forces created by the surrounding stars, the Sun and the planets of the solar system. The force of gravitation exerted on a specific nucleus varies in time, according to their respective orbits. Furthermore, collisions can occur between nuclei within Oort's cloud or Kuiper's belt. These two effects draw some of the nuclei out of their source, toward the Sun or toward the space outside the solar system.

We only know the comets whose perihelion is at distances comparable to those of Jupiter's orbit. Their orbit obeys Kepler's laws (see appendix 12) but is perturbed as

¹ This distance represents slightly less than the distance between the Sun and the nearest star, Proxima Centauri.

they move near to planets. For instance, the period of Lexell's comet changed from 11.4 to 5.6 years in 1770, then to 174.3 years nine years later.

Certain comets have what is known as "short period" orbits i.e. less than 200 years. This is of course the case for the one we know best of all, Halley's comet, which has a period of 76 years, but also for 55 others for which more than one appearance has been observed.

Jupiter, in particular, with its high mass, has a considerable and probably protective effect for the other planets of the solar system. Remember the Shomaker-Levy planet that hurtled toward Jupiter in July 1994 and shattered before impact. The Sun is also a cemetery for a large number of comets, as shown by the SOHO satellite (see chapter 1).

The comet nuclei that near the Sun degas due to the increase in temperature and surround themselves with a "tail" composed of neutral molecules (CO, CN, C₂, C₃, CH, NH₂, OH...) of very low concentration: approximately 10⁴ to 10⁶ cm⁻³. This gas, that is not affected by the interplanetary magnetic field, diffuses into the solar wind over distances that can be as much as 10,000 to 100,000 kilometers. The part of the tail that faces the Sun is called the "coma". On the side opposed to the Sun, the tail splits into what are actually two tails with different physical origins.

The first tail is due to the solar ultraviolet radiation and the bombardment of high energy particles of the solar wind. Under their impact², the tail is excited and ionized on the side of the comet opposed to the Sun, in a way that is quite similar to the atmospheric gas of the Earth (see chapter 2). This creates a plasma coma about which very little is known so far: the comet ionosphere, made up of excited heavy ions. De-energizing takes place in the form of light emission, particularly in the visible: the comet nucleus becomes a comet, acquiring a tail and brilliance. This brilliance increases noticeably during solar eruptive occurrences. The ions formed in the coma are affected by the interplanetary magnetic field and follow it, forming the ion tail.

The second tail of the comet is neutral and is triggered by the interaction between the tail and the low energy solar wind and long wavelength radiation. These have no effect on the comet nucleus, but as they blow they form the neutral comet tail; that is always opposed to the Sun-comet³ direction.

2 On top of these two ionizing processes there is a third process, "critical" ionization discovered by ALFVEN in 1960. The magnetized plasma of the solar wind penetrates the neutral gas of the tail, at a sufficiently high velocity for the kinetic energy of the neutrals in relation to the plasma to become greater than their ionization energy.

3 The photons transport a certain quantity of movement that they transfer to the matter and in relation to the unit of time this gives rise to a pressure if it is also related to the unit of surface. This pressure is called "radiation pressure".

The tails can be several million kilometers long, for a width of less than a million kilometers. They are composed of gas and dust given off by the comet when it degasses. The neutral tail of dust and gas reflects the light of the Sun without emitting any light. It is often a yellowish color. The plasma tail gives off its own radiation, that is characteristic of the ionized elements that compose it. The Archimedes spiral (see chapter 1) of the solar wind plays a part in deforming the plasma tail, giving it a helicoidal shape, whilst the gravity exercised by the Sun deforms the tail of dust.



The Hale-Bopp comet shows up above a green aurora. Its plasma tail can be seen (credit Jon Curtis, Alaska Climate Research Center, Fairbanks, Alaska).

Meteors

Meteors are small rocks, up to a few meters in diameter, that gravitate within the solar system. Meteors and meteorites are known to us because of the falling star phenomenon that occurs as they enter the terrestrial atmosphere: they warm up, becoming incandescent and visible. The nomenclature is somewhat obscure. It is, however, possible to distinguish between meteors that give rise to the falling star phenomenon and fragments of meteors that can be found on the ground. Their impact on the terrestrial environment was mentioned in chapter 2 (the creation of an additional ionospheric layer). Meteors are monitored essentially by means of radar. Good statistics are available, showing great daily and yearly variations.

Like insects, that hit the windshield of an automobile and not the rear window, meteors enter the atmosphere of the Earth on the "front part", along its orbit, i.e. essentially in the morning (maximum 06.00 LT) rather than at dusk (minimum 18.00 LT). Also,

more meteors can be seen in the autumn and when the path of the Earth crosses through a swarm of meteors: the Perseids, (round about August 11th), the Leonids (in November) and other less dense ones that are currents of dust, often produced by the disintegration of comets, traveling round the Sun.

Asteroids

The last of the "small" bodies to be found in the solar system are asteroids. These large rocks, far bigger than meteors, are aborted planets of the solar system. More than 10,000 have been counted but it is estimated that there are several million of them. Ceres, the largest known asteroid, has a diameter of 1003 kilometers. Asteroids can be found in two main regions: a belt situated between the orbits of Mars and Jupiter and Kuiper's belt, that they occupy with the comets, beyond the orbits of Neptune and Pluto. Pluto itself could be a large asteroid in planetary orbit and Charon, its companion, a comet that has finished degassing and has been captured by Pluto⁴.

4 This theory would provide an explanation as to the observations of the Hubble satellite in 1990. According to these, Pluto, with a density of 2.13 ± 0.04 , is composed of three quarters rock and one quarter ice. Charon, with a much lower density (1.30 ± 0.23) is composed essentially of ice.

Appendix 22

ORBITAL PARAMETERS

Just like the planets round the Sun, artificial satellites travel round the Earth following an ellipse described by Keplers' laws (see appendix 12). To find the position of a satellite, we require six parameters that determine its orbit and the way it travels along it.

The orbit itself is determined by three parameters: the apogee radius, the perigee radius and the eccentricity. The apogee radius is the highest distance between the orbit and the Earth, the perigee radius is the lowest distance and the eccentricity of the ellipse characterizes its flatness. The eccentricity is 1 in the case of a straight line and 0 in the case of a circle. It is defined by:

$$\epsilon = \frac{a^2 - b^2}{a^2}$$

where $2a$ is the semi-major axis of the ellipse and $2b$ its semi-minor axis. Its flatness is defined by:

$$\alpha = \frac{a - b}{a}$$

so that:

$$\epsilon = 1 - (1 - \alpha)^2$$

The following figure shows the orbit of a satellite around the Earth. Some of the parameters that define the orbit depend on the reference frame. This is chosen in the following way:

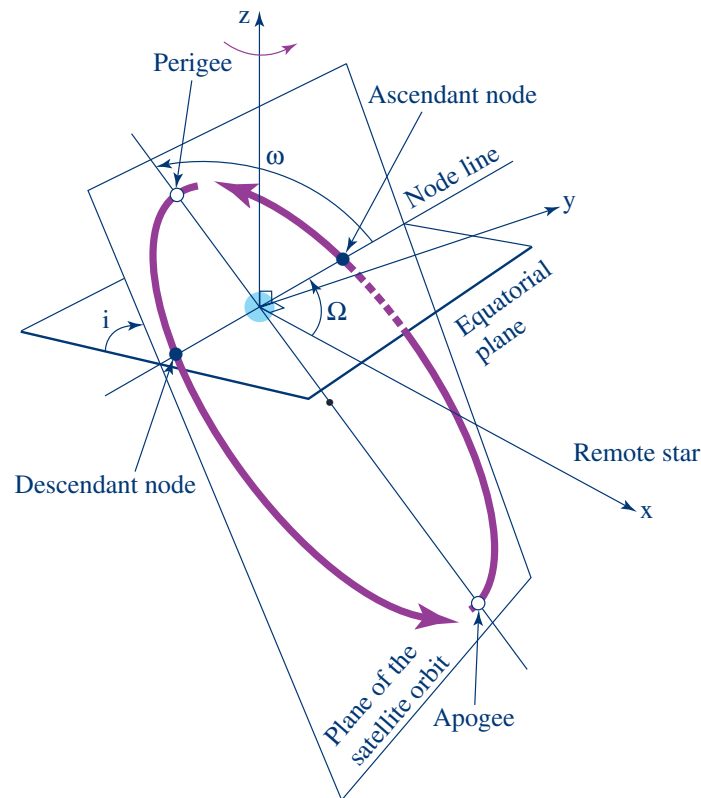
- ♦ the center is the center of the Earth;
- ♦ axis z is that of the geographical poles, i.e. the axis on which the Earth rotates, directed from South to North;
- ♦ plane xOy is the equatorial plane. Axis x is fixed arbitrarily, for instance, by plotting a remote star, and the axis y forms a direct trihedron with Oz and Ox .

As it travels through its orbit, the satellite cuts the equatorial plane Oxy at two points called nodes. The node is ascendant in the South-North hemisphere direction and descendant in the opposite direction (where we can see a representation of the planet showing the hegemony of the northern hemisphere). The straight line that joins the nodes in the equatorial plane is known simply as the node line. Toward the

ascendant node, the node line forms an angle Ω with axis Ox . This is called the right ascension and can vary in time.

The plane containing the orbit forms an angle i , called the inclination, with the equatorial plane. This is 0 in the case of a satellite in equatorial orbit and 90° if the orbit is polar. Since it is calculated in the northern hemisphere, it can be positive or negative (see figure).

Finally, the argument of the perigee ω is the angle formed by the straight line of the semi-major axis (on the perigee side) and the node line.



In order to define the *shape of the orbit*, one can use one of these couples:

- semi-major axis, eccentricity
- perigee radius / apogee radius

One can be deduced from the knowledge of the other. In orbital mechanics, the first one is more commonly used.

In order to define the *position of the orbit*, three parameters are needed:

- inclination
- right ascension of the ascending node
- argument of perigee

The orbit is totally defined by the five preceding parameters. But it is also necessary to define the location of the spacecraft on its orbit. This is made through a sixth parameter, angle between the line of apsides and the center, called true anomaly. One can also use the "mean anomaly", which is the anomaly that the spacecraft would have on a circular orbit of same period, after the same time since the last perigee pass.

In fact, this is a little more complicated, due to the irregularity of the Earth that deforms the ellipse of Kepler's laws. Finally, it is to be noted that the altitude is not an orbital parameter.

The calculation and monitoring of satellite orbits have developed to such an extent that they now bear the generic name of orbitography. This branch, which involves mathematics, geophysics, kinetics and modelization, has its own specific vocabulary. Here are a few terms:

- ♦ The trace is the projection of the orbit on the Earth.
- ♦ The apparent inclination is the angle formed by the trace and the equator. It is, therefore, an angle on the surface of the Earth, different from the orbital inclination described above.
- ♦ Phasing makes it possible to obtain identical filming conditions at regular intervals, called the cycle; the trace is the same but the flight altitudes are not necessarily all identical.
- ♦ An orbit is frozen when the satellite is phased with the same flight altitudes between two orbits.
- ♦ The subsatellite point is the point at which the satellite is projected on the surface of the Earth.

The orbits are named according to certain criteria:

- ♦ *the inclination*
 - if the inclination is close to 0° , the orbit is said to be "equatorial";
 - if the inclination is less than 10° , the orbit is "quasi-equatorial";
 - between 80° and 100° , the orbit is "quasi-polar";
 - at 90° , it is strictly polar;
 - an inclination of less than 90° corresponds to a direct orbit, whereas an inclination of more than 90° corresponds to a retrograde orbit.
- ♦ *the altitude*

Although the altitude is not an orbital parameter, the following orbits can be distinguished:

 - high, i.e. 36,000 kilometers. The English acronym is GEO, for "geostationary";
 - medium, about 20,000 kilometers. The English acronym is MEO, for "Medium Earth Orbit";
 - low, about 1000 kilometers. The English acronym is LEO, for "Low Earth Orbit".

♦ *the location of the satellite*

This concerns the Lagrange L1 point in particular. A satellite in L1 is said to be in a halo orbit, or L1 Lissajous (L1 is unstable and the satellite describes Lissajous curves). The English acronym is L1LO, for "L1 Lissajous Orbit".

♦ *a reference point*

- geostationary: the satellite always flies over the same point of the terrestrial equator, at 36,000 kilometers. It is characterized by its longitude. This orbit is sometimes called "Clarke's orbit";
- flypast, for a non-geostationary satellite;
- heliosynchronous: this is a satellite in low orbit, whose passage at a node is always at the same solar time;
- geosynchronous: the movement of the satellite around the Earth and the movement of the Earth around its axis have the same pulsation;
- with local time drift: non-heliosynchronous.

♦ *eccentricity*

An orbit is circular if its eccentricity is close to 0 (0.01 for instance); otherwise it is elliptic.

Orbits are sometimes named after forerunning satellites. Thus, for very eccentric orbits, we have:

- ♦ Molyna: a very flattened ellipse (a perigee of 400 kilometers and an apogee of approximately 40,000 kilometers that correspond to an eccentricity of 0.75). The English acronym is HEO, for "Highly Eccentric Orbit".
- ♦ Tundra for a non-geostationary geosynchronous satellite.

Appendix 23

SPACE WEATHER INSTRUMENTS

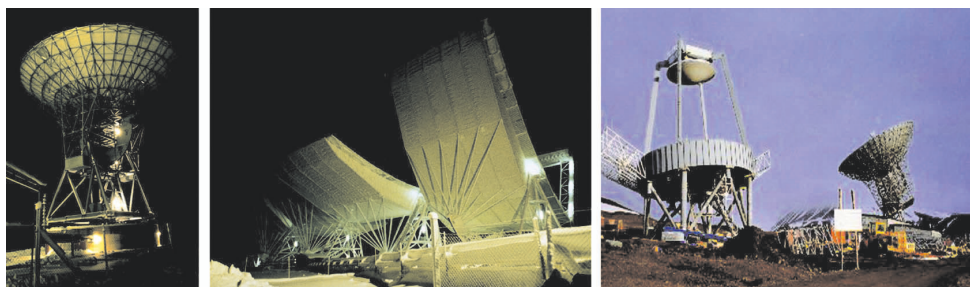
Apart from being thoroughly tedious, a list of all the tools and instruments used for space weather would very soon become obsolete. The object of this appendix is to present the most remarkable of them all.

Instruments at ground level

The most sophisticated technique used to sound the ionosphere is called incoherent scattering. It can be schematized as follows: high frequency radar waves, of several tens to about a thousand megahertz, can pass through the atmosphere. On their path, they force the ions and electrons to rotate around their wave vector at their own frequencies (see appendices 3 and 17). However, during rotation, the particles undergo collisions that accelerate them or slow them down, so that they rotate at frequencies that are distributed over the emission frequency: it is said that the collisions broaden the electromagnetic spectrum. Since the number of collisions varies according to the concentration and the temperature of the medium, the broadening of the spectrum observed by the radar enables the calculation of the temperature of the ions, the electrons and the total ion concentration. The Doppler effect (see appendix 5) also enables the ion velocity to be calculated. These basic parameters are essential for the calculation of many atmospheric magnitudes: heat exchange, particle production... Very few incoherent scatter radars exist. There are two in the United States, one of which is the Porto Rico (Arecibo) giant that has the largest antenna in the world, 300 meters in diameter; one in Peru (under American control, primarily), one in Japan and, above all, the EISCAT radar and their little brother ERS.

EISCAT is situated right in the auroral zone. It has been observing the atmosphere since August 1981, over a band of 10 degrees latitude and an altitude of between 70 and 600 kilometers. It consists of three antennae: the emitter-receiver, a dish with a diameter of 32 meters, functioning at Ultra High Frequency, located in Tromsø (Norway). This emitter gives out a power of 2 megawatts in impulses of a few tens of microseconds. Two receiver antennae of the same size are in Kiruna (Sweden) and Sodankyla (Finland). This set-up, which is the only one of its kind in the world, makes it possible to observe a point of the atmosphere from three different directions. These phenomena are, therefore, studied in three dimensions and not only along the

line of sight. It enables the cofounders (France, Great Britain and Germany for 25% each and the three Scandinavian host countries for the remaining 25% of financial backing) to occupy a special position for the study of space plasmas. As well as this UHF radar, in Tromsø, EISCAT has a 120 meter four-sided antenna which, with its VHF frequency, can take measurements at altitudes of more than 1000 kilometers. On the same spot, a cluster of antennae working at between 4 and 10 megahertz makes it possible to perturb the ionosphere, while the radar observes the responses to this perturbation. Finally, in August 1996, EISCAT inaugurated a double antenna, that functions at 450 megahertz, on the island of Svalbard, right in the polar cusp, at 79° North; this is the inhabited place furthest North on the planet. Japan joined the six founder countries for the latter project, called Eiscat Svalbard Radar (ESR). Optical instruments –fish-eyes camera, or interferometers used, in particular, to observe the red and the green lines of oxygen– complete the set-up.



The 32 meter diameter UHF antenna (on the left) and the four-sided 30 meter wide VHF antenna (center) in Tromsø. On the right, the 32-meter mobile ESR antenna in Svalbard is observing while the 42-meter fixed antenna is still under construction, in July 1999 (credit P. Volcke and C. Lathuillère, Laboratory of Planetology, Grenoble).

SUPERDARN, the international chain of coherent diffusion radars uses a more flexible and less expensive technique. This consists in pointing High Frequency radar perpendicularly to the magnetic field. The wave that is retro-diffused by the ionospheric irregularities gives access to the velocity of the diffusing particles, via the Doppler effect, and to the electric field, using the equation given in appendix 17:

$$\vec{v} = \frac{\vec{E} \wedge \vec{B}}{B^2}$$

In the northern hemisphere, a configuration of nine radars covering 18 local times at high latitudes makes it possible to draw up a chart of the electric fields over almost the whole ice cap, i.e., in terms of velocity, an ionospheric convection chart. These measurements are directly related to the auroral energy that enters the atmosphere, creates atmospheric dilatation and triggers frictional problems on satellites. The importance of SUPERDARN is furthered by the installation of six radar in the southern hemisphere at magnetic points conjugated with those of the

northern hemisphere. In Europe, the principal countries taking part in this international program are Great Britain and France.

Other instruments can be used to probe the ionosphere. Ionosondes send out waves in the megahertz range that rebound in the lower layers of the ionosphere, below the peak of layer F (see chapter 2), enabling particle concentration to be deduced. Instruments such as these are relatively inexpensive and it should be possible to set up a planetary network. However, this is far from true for the time being. Although most countries in Europe and America have them, it is very difficult to capitalize on the results on a global scale: they are not gauged with each other and the part played by the experimenter is essential. In most countries, unfortunately, it is difficult to take daily measurements and send them to a coordination center.

The same applies to GPS ground receiving stations (see chapter 3). Only four out of the existing network are automated. The sorting programs that make it possible to switch from the signal to the electronic content of the atmosphere are not gauged and we are up against the same problems as those encountered with ionoprobes.

Networks of magnetometers have been set up to obtain the geomagnetic state. They measure the magnetic perturbations continuously and give precise data as to whether a magnetic storm or substorm is taking place. At low latitudes, they give data concerning the radiation belts (see chapter 2), making it possible to draw up the magnetic indexes that are so important to the digital programs of space weather. At high latitudes, their measurements give direct signatures of the atmospheric currents that affect certain users: electricity, gas or oil companies... Nowadays, 150 magnetic observatories are in operation throughout the world; 76 are linked in a network (INTERMAGNET). The Scandinavian part is called IMAGE.

In spite of the atmospheric cover, it is possible to observe the Sun from the ground. THEMIS (Heliographic Telescope for the Study of Magnetism and Solar Instabilities) is a Franco-Italiano-Spanish telescope located on the island of Tenerife. It is an ultra-modern telescope that can measure the magnetic field in several directions and has spatial, spectral and temporal high resolution, obtained by means of several complementary methods of observation.



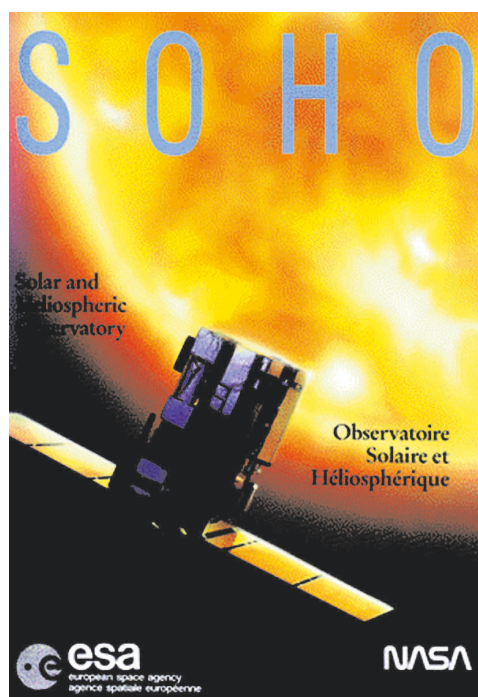
Radio antennae, like the large antenna in Nançay, Sologne (France) observe the solar corona and the transition region, enabling coronal mass ejections to be detected. Analysis of the magnetic field throughout the disk give an idea as to the global variation of solar activity. Spectrographs that function in the wavelengths that penetrate down to ground level (essentially in the visible) allow permanent analysis of solar emission lines (see chapter 1). Observation in the radio range, in particular, gives indications about solar activity that is valuable for the estimation of the extreme ultraviolet flux through measurement of index $f_{10.7}$.

Instruments in space

Here again we shall only present a few space instruments, those which played the greatest part in obtaining the results given in this book. For observation of the Sun, various space probes are invaluable:

SOHO: Solar Heliospheric Observatory. The SOHO satellite is the result of close cooperation between its prime contractor, the European Space Agency (ESA), and NASA. It was launched in December 1995. Nine instrument supervisors or Principal

Investigators (PI's) are European and three are American. Mission control is carried out from the MEDOC Center, at the Institute for Space Astrophysics, close to Paris and the GSFC in Maryland, United States. SOHO has a continuous view of the Sun, thanks to its orbit around the L1 Lagrange point, 1.5 million kilometers in front of the Earth, where the gravities of the Earth and of the Sun and the centrifugal force offset each other. The scientific advances made possible by this satellite are innumerable. Solar physics now has distinct eras: before and after the contribution of nuclear physics, then before and after SOHO.



SOHO faces the Sun (credit NASA)

TRACE: a small satellite developed by the Lockheed Institute in Stanford (USA) to observe the evolution of the magnetic structures of the Sun. It could be described as "SOHO's little brother" with regard to the composition of the instruments on board and the quality of its observations. Although it is less comprehensive, it observes the solar corona and the transition region to try to solve the mystery of corona heating

and the mechanisms that precede a solar eruption or a coronal mass ejection. The resolution of its pictures of coronal magnetic loops is unequalled.

ULYSSES: ULYSSES, under the supervision of the ESA and in cooperation with NASA, is a satellite designed to explore the region of space that is under the influence of the solar wind, by observing it from all the solar latitudes. This satellite has been operational since it was launched in October 1990. Its path first sent it toward Jupiter, at 5.4 AU, where it left the ecliptic plane, and then back toward the Sun. It reached the highest latitudes in September 1994 (slightly more than 80° solar latitude South) and July 1995 (80° North). In November 1997, it finished its first rotation around the Sun, at a distance of approximately 1.3 AU, i.e. beyond the orbit of the Earth.

YOHKOH: YOHKOH is a satellite that operates in the ranges of X-rays and gamma rays. It was launched in August 1991 and was implemented by the Japanese Institute of Spatial and Aeronautical Science, with British and American contributions. The range of radiation chosen for observation makes it possible to study high energy phenomena in eruptions and the solar corona. It revealed large-scale dynamics of the solar corona and allows precise observation of the evolution of coronal holes. YOHKOH was lost in December 2001.

The study of the solar wind is based mainly on the *WIND* satellite. WIND was launched on November 1st 1994 and was sent into orbit around the L1 Lagrange point. It is part of the ISTP project (see appendix 24). The purpose of this satellite is to establish a complete description of the solar wind, whether in the form of plasma, energized particles or the interplanetary magnetic field. Its position between the Earth and the Sun means that it is a kind of sentinel, capable of giving a few hours' advance warning of a magnetic storm.

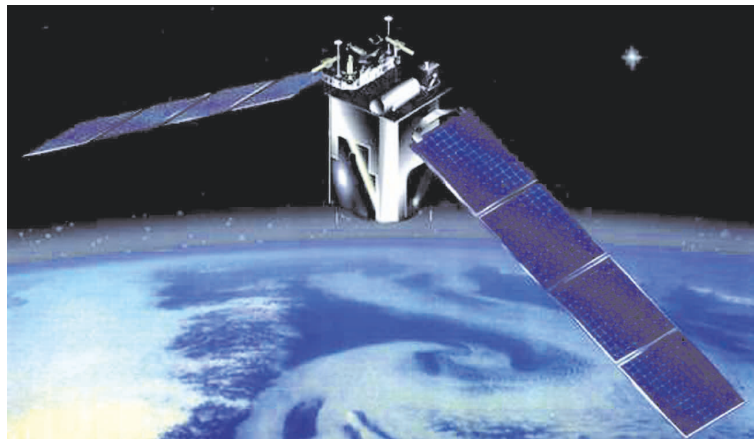
In the magnetosphere, the jewel in our collection is called *CLUSTER*. The CLUSTER mission consists of four satellites carrying identical instruments. Put into a very flat orbit (between 4 and 19.6 terrestrial radii from the perigee to the apogee), they fly in formation at the summit of a tetrahedron of adjustable dimensions. Each satellite weighs 1200 kilograms; more than half of the weight is made up of ergols used to position and control flight in formation. It is in the form of a cylinder with a diameter of 2.9 meters and 1.3 meters high. Power is supplied to the instruments by means of solar cells distributed around the satellite (224 Watts at the end of its life). Its payload comprises eleven instruments designed to measure the magnetic field, waves and particles. CLUSTER underwent a serious hitch: the four satellites, secured in the cap of the first Ariane 5 test flight, were destroyed along with the rocket shortly after lift-off. The considerable importance of the scientific mission convinced the European space authorities to implement CLUSTER II, which was launched in 2000. The first results confirmed the intuitions concerning the relevance of this flight in formation: recently we have had a four-dimensional view of the magnetosphere,

which is radically different from all we had imagined before (see chapter 2). CLUSTER is backed up by two other crafts: GEOTAIL and POLAR.

GEOTAIL corresponds to a joint mission between the Japanese ISAS and the American NASA, assigned to the study of the magnetospheric tail over a distance ranging from 8 terrestrial radii (from its launching in July 1992 up to 1995) and 200 terrestrial radii (since 1995). A major part of the concepts explained in chapter 2 concerning this part of the magnetosphere were confirmed or established thanks to this satellite.

POLAR, another of the ISTP tools, was launched in February 1996. Its purpose is to obtain data concerning energy transfers between the solar wind and the magnetosphere through the polar cusps and the manner in which this energy is transformed in the auroral ionosphere (auroras, creation of electric fields...). When it passes through low latitudes, *POLAR* measures the radiation belts. The most spectacular pictures of the auroral oval to date were obtained by this satellite, in the ultraviolet, in particular, and in five frequencies in the visible. It has a very elliptic orbit, with an apogee at 9 terrestrial radii, a perigee at 1.8 terrestrial radii and an inclination of 86 degrees.

To date, there were few thermospheric observations by satellite. The American probe *TIMED*, launched on December 7 2001, fills this gap. With this satellite, NASA hope to obtain the first data proving a link between thermospheric and climatic phenomena, in the context of global warming of the planet. *TIMED* is the acronym of Thermosphere-Ionosphere-Mesosphere-Energy-Dynamics. From its altitude of 625 kilometers, its field of observation ranges from 60 to 180 kilometers above ground level; this region is of utmost importance since it concerns telecommunications, satellite monitoring, friction on satellites and the reentry of spacecraft.



The TIMED satellite, due to be launched at the end of 2001 (credit NASA)

Space weather?

Except for the GPS system, the vocation of the instruments we have described is essentially scientific. Their purpose is to widen our knowledge and comprehension of the Sun-Earth system. They cannot fulfil the requirements of an operational space weather service. This would mean continuous and global monitoring (on both the day side and the night side of the Earth), entailing multi-satellite networks and ground instruments distributed over a sufficiently dense grid and accurately gauged.

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<http://www.solar.isas.ac.jp/english/index.html>

<http://lep694.gsfc.nasa.gov/waves/waves.html>

A FEW USEFUL CONSTANTS

1. Physical constants

Velocity of light in vacuum	$c = 2,998 \times 10^8 \text{ m s}^{-1}$
Gravitational constant	$G = 6,673 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
Planck's constant	$h = 6,6256 \times 10^{-34} \text{ J s}$
Boltzmann's constant	$k = 1,381 \times 10^{-23} \text{ J K}^{-1}$
Electron rest mass	$m_e = 9,109 \times 10^{-31} \text{ kg}$
Proton rest mass	$m_p = 1,675 \times 10^{-27} \text{ kg}$
Fundamental charge	$e = 1,602 \times 10^{-19} \text{ C}$
Magnetic permeability of vacuum	$\mu_0 = 12,566 \times 10^{-7} \text{ H m}^{-1}$
Dielectric permittivity of vacuum	$\epsilon_0 = 8,854 \times 10^{-12} \text{ F m}^{-1}$
Stefan's constant	$\sigma = 5,67 \times 10^8 \text{ W m}^{-2} \text{ K}^{-4}$

2. Geophysical constants

Mean Earth radius	$6,371 \times 10^6 \text{ m}$
Equatorial Sun radius	$696 \times 10^6 \text{ m}$
Mean distance between the Earth and the Sun (AU)	$1,496 \times 10^{11} \text{ m}$
Solar constant	$1366,1 \text{ W}$

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WORD GLOSSARY

> **Active region prominence**

streamers of solar matter that can reach an altitude of 10,000 kilometers. The magnetic field in a prominence can be as high as about 50 Gauss (5×10^{-3} T) (see *filament*).

> **Aeronomy**

field of astronomy dealing with the specific study of the intermediate and high planetary atmospheres.

> **Albedo**

fraction of the incident light and energy that is reflected or diffused by a non-luminous body. The albedo is always comprised between 0 and 1. It varies according to the wavelength. An albedo equal to zero at a given wavelength characterizes a body that absorbs all this radiation perfectly. A value of 1 characterizes a perfect mirror for that wavelength.

> **Aligned current**

electric current aligned on the magnetic field lines. In the ionosphere, they can be found at high latitudes, in the auroral oval.

> **Andromeda nebula**

galaxy similar to ours (the Milky Way) in our local cluster.

> **Aphelion**

furthest point from the Sun in the orbit of a body revolving around the Sun.

> **Apogee**

furthest point from the Earth in the orbit of a body revolving around the Earth.

> **Archimedes spiral**

geometric figure, the typical example of which is the trajectory described by water spraying out of a rotating garden sprinkler.

> **Asteroid**

small planet of less than a few hundred kilometers. A belt of several thousand asteroids stretches between Mars and Jupiter, at an average distance of between 2.17 and 3.3 AU from the Sun.

> **Astronomical Unit**

average distance between the Sun and the Earth, i.e. 1,495,978,710 meters.

> Auroral oval

zone in which ionized particles are precipitated from the magnetosphere toward the thermosphere. At all times there is one oval in the North and another in the South. It generally ranges from 65° to 75° in latitude, but can spread during magnetic storms or substorms.

> Big-Bang

according to the "standard" cosmological model, a simultaneous explosion throughout space that is at the origin of our universe.

> Blue jet

blue lightning connecting the low atmosphere and the terrestrial ionosphere.

> Brown dwarf

star whose mass is too low for nuclear reactions to take place.

> Chromosphere

region of sun's atmosphere, above the photosphere and below the corona, characterized by a sudden increase in temperature. During a total eclipse of the Sun it shows up as a thin, bright pink layer, hence its name. The color is due primarily to the hydrogen emission line at 656.3 nanometers. On the Sun, it has a depth of approximately 10,000 kilometers.

> Chromospheric plage

zone of the chromosphere in which the field lines of a spot favor the dissipation of energy toward the immediate atmosphere, giving rise to hot atmospheric zones that can reach into the solar corona.

> Circular (orbit)

satellite orbit whose eccentricity is close to zero.

> Comet

body of the solar system, consisting of a solid nucleus made up of rock and ice. There are two comet sources: the Oort Cloud and the Kuiper's Belt. As they near the Sun, comets give off an atmosphere in the form of two tails, one neutral and one ionized.

> Convection

transfer of thermal energy via fluid currents (gases or liquids).

> Convection zone

external region of the inside of the Sun, where the energy produced by the nuclear core is transmitted by convection. This is the region where solar matter seethes.

> Coronagraph

optical instrument simulating an eclipse.

> Coronal hole

region of the solar corona where the magnetic field lines open into space allowing the solar wind to escape.

> Coronal mass ejection

sudden mass ejection from the Sun, in the widest sense.

> Coronal streamer

ejection of solar gas from the corona.

> Cosmic ray

high energy particle from stars other than the Sun.

> Corotation

joint rotation of the atmosphere and a planet.

> Cross-tail current

electric current created by the separation of charges in the magnetosphere tail (night side of the Earth).

> Current ring

zone of the magnetosphere, at an altitude of more than four terrestrial radii, through which ions and electrons travel due to the combined effect of the gravitational and geomagnetic fields.

> Declination

arc of a meridian between a point on the surface and the point on the equator.

> Eccentricity

parameter of an ellipse that characterizes its flatness. Eccentricity is equal to 1 in the case of a straight line and to 0 in the case of a circle.

> Ecliptic

plane in which the Earth orbits the Sun.

> Elliptic (orbit)

satellite orbit of low eccentricity.

> Equatorial (orbit)

satellite orbit whose inclination is close to 0° ; quasi-equatorial orbits have inclination smaller than 10° .

> Ergol

fuel used in the composition of a propellant.

> Exosphere

upper zone of the heterosphere where the temperature is constant.

> Exospheric temperature

temperature of the thermosphere above 400 kilometers.

> Facula

a region or spot that is brighter than the rest of the solar surface.

> Fibrille

dark, elongated structure on the solar corona, that probably forms a boundary with the chromospheric magnetic field.

> Filament

long structure that can be seen on the Sun near magnetic field reversal lines. When observed against the bright surface of the Sun, a filament appears darker since it is colder. When observed on the limb of the Sun, as it passes through the less luminous solar atmosphere, it appears to be bright (see *prominence*).

> Flypast

non-geostationary satellite.

> Galaxy

group of stars, dust and interstellar gas, isolated in space, whose cohesion is maintained by gravity.

> Geographic pole

intersection between the rotation axis of any heavenly body and its surface.

> Geomagnetic field

magnetic field of the Earth.

> Geostationary (orbit)

satellite orbit that always flies over the same point of the terrestrial equator. Geostationary satellites are on what is called a "high orbit", at 36,000 kilometers.

> Geosynchronous

satellite that orbits the Earth with the same frequency as the movement of the Earth around its axis.

> Giant planet

refers to Jupiter, Saturn, Uranus and Neptune.

> Granulation

bright structure on the solar photosphere, that shows up as a cell with a mean diameter of 1,200 kilometers and an average life span of 18 minutes. In between granulations, the matter appears darker. These granulations correspond to the seething of the convective zone.

> Heliosphere

region in space that undergoes the influence of the solar wind. It spreads from approximately 50 to 100 AU from the Sun.

> Heliosynchronous

satellite in low orbit that always passes over a node at the same solar time.

> Heterosphere

zone of the Earth atmosphere typically located above 80 kilometers, where each of the constituents has its own scale height since each of them has its own pressure decrease rate.

> **High Earth Orbit**

see *geostationary*.

> **Homopause**

upper boundary of the homosphere, at an altitude of about 80 kilometers.

> **Homosphere**

all the lower layers of the terrestrial atmosphere in which the scale height is the same for all the constituents: the pressure and concentration decrease rates follow the same law for all. The homosphere ends at an altitude of about 80 kilometers.

> **Inclination**

angle between the plane in which a body orbits and the equatorial plane.

> **Intermediate Earth Orbit**

satellite orbit at about 20,000 kilometers from the Earth.

> **Interplanetary magnetic field**

magnetic field carried by the solar wind.

> **Ionosphere**

gas consisting of charged particles (ions and electrons) that mingles with the thermosphere to form the high altitude atmosphere.

> **Jansky**

see *solar flux unit*.

> **Kinetic pressure**

pressure exerted by a gas.

> **Kuiper belt**

a second source of comets and small solar system bodies, shaped as a flat ring stretching from the orbits of Neptune and Pluto to the internal boundary of Oort's Cloud. It is thought that it could contain more than ten times as many comet nuclei as Oort's Cloud.

> **Lagrange point**

zones in space where the gravity of two bodies and the centrifugal force balance out. There are 5 of them. Here we only consider point L1 which is between the Sun and the Earth.

> **Latitude**

angular distance from the equator in a spherical coordinate system.

> **Legal time**

time defined by each country.

> **L1 halo or L1 Lissajous**

satellite orbit around the L1 Lagrange point.

> **L1LO**

L1 Lissajous Orbit, see *L1 halo*.

- > **Limb**
bright edge of the disk of a heavenly body.
- > **Local time**
marked *LT*.
- > **Longitude**
angular distance along a parallel, calculated from a source meridian in a spherical coordinate system.
- > **Low Earth Orbit**
satellite orbit at an altitude of about 1,000 kilometers above the Earth.
- > **Macrospicule**
solar matter ejected permanently between the supergranules, in the form of proton and electron tongues.
- > **Magnetic cloud**
front of a coronal mass ejection, once it has reached space.
- > **Magnetic declination**
angle between the magnetic meridian and the geographic meridian at a given point.
- > **Magnetic mirror**
phenomenon that transfers energy related to parallel movement to the field lines into energy related to perpendicular movement; as a result, the particles slow down, stop and then reverse when they enter the zones where the field lines close in.
- > **Magnetic pole**
region on a body where magnetic inclination is maximum.
- > **Magnetic pressure**
pressure exerted by magnetic forces.
- > **Magnetic storm**
considerable perturbation of the geomagnetic field due to its interaction with the interplanetary magnetic field. Storm: the effect is planetary. Sub-storm: it is confined to high latitudes.
- > **Magnetopause**
boundary between the magnetosphere and the solar wind.
- > **Magnetopause current**
current created by the separation of solar wind charges on the magnetopause.
- > **Magnetosheath**
zone on the terrestrial magnetic field where the solar wind is compressed.
- > **Magnetosphere**
cavity inside which the geomagnetic field controls the plasma and is relatively protected from the solar wind.

> **Maunder minimum**

period during which practically no sunspots were observed (from 1645 to 1715).

> **Meridian**

site where the points are all at the same longitude on the surface of the Earth or on any other heavenly body.

> **Mesopause**

boundary between the mesosphere and the thermosphere.

> **Mesosphere**

region of the Earth atmosphere situated between approximately 50 to 80 kilometers in height.

> **Meteor**

fragment of rock that travels through space and enters the terrestrial atmosphere where it heats, triggering the falling star phenomenon.

> **Meteorite**

fragment of a meteor found on the ground.

> **Micro-wave**

marked *SHF*.

> **Milky Way**

name of our galaxy.

> **Molnya**

satellite orbit describing a very flat ellipse (a perigee of about 400 kilometers and an apogee of about 40,000 kilometers).

> **Neutral sheet (or plasma sheet)**

zone of the night side magnetopause, where the solar wind ions and electrons meet up.

> **Neutrino**

fundamental particle with no electric charge and very low mass.

> **Nuclear core**

center of a star, the seat of the nuclear fusion reactions that produce the energy radiated by the star.

> **Nuclear oven**

core of the Sun, in which nuclear fusion maintains constant generation of energy (see *nuclear core*).

> **Nucleosynthesis**

formation of chemical elements by nuclear reactions in the core of stars or in the first few moments after the big-bang.

> Oort cloud

one of the comet sources, on the border of the solar system –at about 20,000 AU¹. It is a tenuous sphere whose existence was first conjectured in the 1950s. It is estimated that this cloud contains between 100 and 1,000 billion comet nuclei.

> Ozone

molecule consisting of three atoms of oxygen.

> Parallel

a location where all points are at the same latitude on the surface of the Earth or of any other body.

> Perigee

the point in its orbit where a satellite traveling round the Earth is closest to the Earth.

> Perihelion

the point in its orbit where a body traveling round the Sun is closest to the Sun.

> Photon

fundamental corpuscle binded with electromagnetic waves.

> Photosphere

surface of the Sun that is visible in white light. The major part of solar radiation comes from the photosphere and a very small part from the corona.

> Planetary nebula

cloud of gas in expansion around the residue of a white dwarf.

> Plasma

gas in which charged particles (ions, electrons) are free. In geophysics, the plasma are neutral, i.e. there are just as many electrons as there are monovalent ions.

> Plasmopause

external boundary of the plasmasphere.

> Plasmasphere

zone of the magnetosphere that co-rotates with the Earth.

> Plume

streamers of solar matter above the coronal holes.

> Polar light

luminous atmospheric phenomenon (boreal in the northern hemisphere, austral in the southern hemisphere) due to the de-energizing of atmospheric gas excited by collisions with solar wind particles.

¹ This represents slightly less than the distance between the Sun and the nearest star, Proxima Centauri.

- > **Polar circle**
latitude beyond which the Sun does not rise at least one day per year (or does not set at least one day per year).
- > **Polar cusp**
zone of the magnetosphere where the geomagnetic field lines open out onto the magnetosheath and into space.
- > **Polar (orbit)**
satellite orbit with an inclination of 90°.
- > **Positron**
antiparticle of the electron, with a positive charge.
- > **Propellant**
product composed of one or several ergols, producing the energy required to propel a rocket engine, via chemical reaction.
- > **Quasi-polar (orbit)**
satellite orbit with an inclination of between 80° and 100°.
- > **Quiescent prominence**
quiet Sun prominence, rising to an altitude up to 100,000 kilometers with a magnetic field of about ten Gauss (10^{-3} T).
- > **Radiative zone**
internal region of the Sun, between the nuclear oven and the convection zone. Here, the energy produced by the nuclear core is transmitted by radiation.
- > **Reconnection point**
zone of the magnetosphere, on the night side, where the plasma sheet encounters the magnetopause.
- > **Red giant**
star in which hydrogen combustion in the nuclear core has finished; the helium heart becomes denser and hotter than it was originally and the shell dilates (up to about 100 times its original size).
- > **Ring current**
an electric current that creates a ring at a low latitude around the Earth, at between four and seven terrestrial radii from the surface of the planet.
- > **Schwabe cycle**
cycle of solar activity, lasting between 10 and 12 years.
- > **Shockwave**
in the field of aeronomy, corresponds to the solar side of the magnetopause.
- > **Sidereal rotation**
rotation of the Sun (or a heavenly body) observed from a fixed point in the solar system.

> **Solar constant**

total solar power received by a surface one meter square, perpendicular to the solar radiation, at a distance of 1 AU (1366.1 Watts per square meter).

> **Solar corona**

high temperature region of the solar atmosphere, above the chromosphere; here, plasma is trapped by the local magnetic field or escapes into space if the magnetic field lines are open.

> **Solar eruption**

mass ejection from the Sun, related to a prominence.

> **Solar flux unit**

unit used to measure the solar flux, especially the $f_{10.7}$ index (10^{22} W m⁻² Hz⁻¹).

> **Solar wind**

particle flux related to the interplanetary magnetic field. It is composed primarily of electrons and protons (expelled continuously from the Sun toward space).

> **Solar wind (fast)**

solar wind ejected above the coronal holes or during eruptions (speeds of roughly 700 to 950 km s⁻¹).

> **Solar wind (slow)**

solar wind ejected above the quiet photosphere (speeds of roughly 300 to 450 km s⁻¹).

> **Spicule**

solar matter expelled permanently between the granules, in the form of proton and electron tongues.

> **"Sprite"**

red flash linking the low atmosphere and the ionosphere of the Earth.

> **Star**

luminous gaseous heavenly body, in the core of which nuclear fusion takes or used to take place.

> **Stratopause**

upper boundary of the stratosphere.

> **Stratosphere**

region of the atmosphere between the troposphere and the mesosphere, at an approximate altitude of 12 to 50 kilometers.

> **Submillimetric**

radio wave with a frequency of between 300 GHz and 1 THz.

> **Subsolar point**

area of the magnetosphere situated on the imaginary line between the center of the Sun and the center of the Earth.

> Supergranulation

large-size granulation (30,000 kilometers).

> Supernova

stage in the life of a massive star, characterized itself by an explosion that makes it extremely bright for a while.

> Sunspot

dark zone of the photosphere, with a mean diameter approaching a few thousand kilometers. The spots are areas with a strong magnetic field and they look dark because they are colder than the photosphere.

> Synodic rotation

rotation of the Sun observed from the Earth, i.e. taking into account the Earth's own rotations (on its axis and around the Sun).

> Telluric planet

refers to the solar system planets which are similar to the Earth in size and composition: Mercury, Venus and Mars.

> Thermosphere

zone where the temperature of the neutral terrestrial atmosphere increases, at an altitude exceeding about 80 kilometers.

> Transition region

region of the solar atmosphere, between approximately 3,000 kilometers and forty-thousand kilometers, where the temperature increases from 10,000 degrees to more than 1 million degrees.

> Troposphere

region of the atmosphere closest to the ground, whose depth increases between the pole (8 kilometers) and the equator (17 kilometers).

> Tundra

orbit of a non-geostationary geosynchronous satellite.

> Universal Time

marked *UT*.

> Van Allen's (radiation) belts

zones in the magnetosphere surrounding the Earth in which highly energized particles are trapped.

GLOSSARY OF NAMES, ACRONYMS AND LOGOS

> **Ap**

index of magnetic activity (Planetary Amplitude).

> **BASS 2000**

"BAsse de données Solaires (Solar Data Base) Sol 2000" dedicated to solar observations obtained on the one hand via instruments at ground level and, on the other hand, through simulations or digital extrapolations concerning solar physics.

<http://mesola.obspm.fr>

> **CDS**

"Coronal Diagnostics Spectrometer", a solar observation instrument on the SOHO satellite.

<http://solg2.bnsc.rl.ac.uk/>

> **CLUSTER**

constellation of four satellites launched in 2000 to study the terrestrial magnetosphere. This is a ESA-NASA project.

<http://sci.esa.int/cluster/>

> **EHF**

Extra High Frequency, radio wave whose frequency is between 30 and 300 GHz.

> **EIT**

Extreme ultraviolet Imaging Telescope, solar observation instrument on the SOHO satellite.

<http://umbra.nascom.nasa.gov/eit/>

> **ELF**

Extra Low Frequency, radio wave whose frequency is between 10 Hz and 3 kHz.

> **ESA**

European Space Agency.

<http://www.esrin.esa.it/export/esaCP/index.html>

> **f_{10.7}**

decimetric index, measurement of the solar emission flux at 10.7 cm (expressed in $10^{22} \text{ W m}^{-2} \text{ Hz}^{-1}$).

> FOC

"Faint Object Camera" on board the Hubble Space Telescope (ESA).

> GEO

Geostationary Earth Orbit, see *geostationary*.

> GIC

Geophysical induced current.

> GSFC

Goddard Space Flight Center, a NASA center.

<http://www.gsfc.nasa.gov/>

> HEO

Highly Eccentric Orbit, see *Molnya*.

> HF

High Frequency, radio wave whose frequency is between 3 and 30 MHz.

> IGRF

International Geomagnetic Reference Field, an empiric model of the geomagnetic field.

<http://www.ngdc.noaa.gov/stp/stp.html>

> ISAS

Institute of Space and Astronautical Science, Japanese space and space weather agency.

<http://www.isas.ac.jp/e/>

> ISTP

International Solar Terrestrial Physics. A program created jointly in 1980 by three space agencies, NASA, ESA and ISAS. The aims of the ISTP are essentially scientific: to determine the structure and dynamics of the interior of the Sun, understand solar activity, corona heating, the acceleration of the solar wind, the interplanetary medium, the impact on the terrestrial atmosphere and the magnetosphere. This program develops space instruments and theoretical models.

<http://www-istp.gsfc.nasa.gov/>

> Kp

index of magnetic activity.

> LEO

Low Earth Orbit, see *low (orbit)*.

> LF

Low Frequency, radio wave whose frequency is between 30 and 300 kHz.

> LPARL

Lockheed Martin Palo Alto Research Lab.

<http://www.lpl.arizona.edu/>

> LT

Local Time, the time in relation to the Sun where the observer is located.

> MDI

"Michelson Doppler Interferometer". This is an optical instrument (interferometer) on board the SOHO satellite, that takes Doppler pictures of the Sun.

<http://soi.stanford.edu/>

> MEDOC

SOHO data and control center.

<http://www.medoc-ias.u-psud.fr/>

> MEO

Medium Earth Orbit, see *medium (orbit)*.

> MF

Medium Frequency, radio wave whose frequency is between 300 kHz and 3 MHz.

> MSIS

Mass-Spectrometer-Incoherent-Scatter (MSIS) model, or international model of the high terrestrial atmosphere. The MSIS-E version also covers the ground.

<http://nssdc.gsfc.nasa.gov/space/model/models/msis.html>

> NASA

American space agency, "National Aeronautic and Space Administration".

<http://www.nasa.gov/>

> NGDC

National Geophysical Data Center, in USA.

<http://www.ngdc.noaa.gov/>

> NORAD

North American Aerospace Defense Command. This is a binational (USA-Canada) control center, charged with warning of attack by aircraft (or missile) of either of these countries and organizing air defense in the case of such an attack.

<http://peterson.af.mil/norad>

> RI

index of monthly sunspots.

> RI₁₂

average index of monthly sunspots.

> SEC

Space Environment Center.

<http://sec.noaa.gov>

> SEU

Single Event Unit.

> SHF

Super High Frequency, radio wave whose frequency is between 3 and 30 GHz.

> Skylab

the first American space station.

<http://ssl.msfc.nasa.gov/ssl/pad/solar/skylab.htm>

> SOHO

SOLar Heliospheric Observatory.

<http://sohowww.estec.esa.nl>

> THEMIS

Heliographic Telescope for the Study of Magnetism and Solar Instabilities.

<http://www.themis.iac.es/>

> TRACE

small satellite developed by the Lockheed Institute in Stanford (USA) to observe the evolution of the magnetic structures of the Sun.

<http://vestige.lmsal.com/TRACE/>

> UHF

Ultra High Frequency, radio wave whose frequency is between 300 MHz and 3 GHz.

> ULF

Ultra Low Frequency, radio wave whose frequency is lower than 10 Hz.

> ULYSSES

satellite developed to explore the region in space that is exposed to the solar wind, by observing it at all the solar latitudes for the first time (ESA-NASA).

<http://sci.esa.int/ulysses/>

> UT

Universal Time, reference time of all countries of which the origin is the Greenwich's meridian.

> UVCS

Ultraviolet Coronagraph Spectrometer on board SOHO.

<http://cfa-www.harvard.edu/uvcs/>

> VHF

Very High Frequency, radio wave whose frequency is between 30 and 300 MHz.

> VLF

Very Low Frequency, radio wave whose frequency is between 3 and 30 kHz.

> WFPC2

a second wide-field camera for studying planets ("Wide Field Planetary Camera 2"), on the Hubble space telescope (NASA).

> WIND

NASA satellite for observing the solar wind, located near the Lagrange L1 point.

<http://lep694.gsfc.nasa.gov/waves/waves.html>

> YOHKOH

Japanese solar observation satellite that operated since December 2001 in the X-ray and γ ray ranges.

<http://www.solar.isas.ac.jp/english/index.html>

INDEX

A

active period	29
adiabatic invariant	184
aeronomy	93
albedo	58
aligned currents	79
amount of light	155
apogee	205
apparent inclination	207
Archimedes' spiral	188
ascending node	206
astronauts	115
attitude controls	107
auroral oval	80

B

big bang	2
blackbody	18,157
blue jets	89
Boltzmann	
– constant	136
– law	136
brightness	154

C

carbon-nitrogen cycle	139
chromosphere	25
chromospheric plages	33
climate	117
comets	201
constellations	108
convection zone	11,15
Coriolis' force	167
corona	42
coronagraph	40

coronal

– holes	38
– mass ejection	42,47,121
corotation	77
cosmic rays	79,118
cross-tail current	76
current density	145
cusps	79
cyclotron frequency	164

D

Dalton minimum	29
decimetric index	45
declination D	56,58
degree of freedom	136
dipolar magnetic field	147
dipole	56
dissociation	63,181
doppler effect	150
dwarf	
– black	6
– white	6

E

Earth	51
eccentricity	205
electric	
– current	69
– field	70,141
– generator	95
electrical networks	94
electromagnetic wave	160
emittance	154
equation	
– of Faraday	142
– of Poisson	141

- | | | | |
|------------------------------|-----------|-------------------------------------|-------------|
| equatorial plane | 205 | International Geophysical Year | 92 |
| excitation | 63,181 | International Space Station | 112 |
| exposure | 155 | Interplanetary magnetic field (IMF) | 20 |
| extreme ultraviolet | 62 | ionization | 63,182 |
| | | ionosphere | 63 |
| F | | | |
| falling sky | 118 | J | |
| fast solar wind | 38 | Jansky | 46 |
| fibrilles | 26 | Jupiter | 192 |
| field-aligned currents | 77 | | |
| filament | 33 | K | |
| flares | 47 | Kepler's laws | 171 |
| flatness | 205 | kinetic | |
| flight crew | 116 | – energy | 135,166,187 |
| frozen plasma | 165 | – pressure | 166,187 |
| G | | | |
| geographical | | L | |
| – coordinates | 53 | Larmor's radius | 164 |
| – equator | 53 | launch (rocket) | 101 |
| – poles | 53 | liquid nucleus | 54 |
| geomagnetic field | 53 | local time | 53 |
| geophysical induced currents | 95 | Lorentz force | 70,185 |
| global positioning systems | 98 | luminance L | 153,159 |
| granules | 15 | | |
| Greenwich | 53 | M | |
| H | | | |
| Hales polarity law | 29 | macrospicules | 24 |
| heating | 66 | magnetic | |
| heterosphere | 61 | – field | 141,163 |
| homosphere | 58,60 | – of the Sun | 32 |
| human eye | 156 | – induction | 141 |
| | | – mirror | 185 |
| | | – pressure | 166 |
| | | – shell | 76 |
| | | – storm | 87 |
| | | – sub-storm | 87 |
| I | | magnetopause | 71 |
| inclination I | 56,58,206 | magnetosphere | 68,71,86 |
| index | 177 | Mars | 191 |
| infrared | 161 | mass | 3 |
| inner belt | 78 | Maunder minimum | 29 |
| insurance companies | 119 | Maxwell's equations | 141,146 |
| intensity | 154 | | |

- | | | | |
|--------------------------------------|-------------|----------------|--|
| Maxwell-Ampère's theorem | 142 | | |
| McIllwain parameter | 56,58 | | |
| Mercury | 190 | | |
| meridians | 53 | | |
| mesosphere | 60 | | |
| meteors | 203 | | |
| Moon | 198 | | |
|
 | | | |
| N | | | |
| Neptune | 196 | | |
| neutrinos | 13 | | |
| nuclear | | | |
| – oven | 11 | | |
| – reaction | 138 | | |
| nucleosynthesis | 6 | | |
| nutatation | 175 | | |
|
 | | | |
| O | | | |
| outer radiation | 76 | | |
| oxygen | | | |
| – green line | 66 | | |
| – red line | 66 | | |
| ozone | 60 | | |
|
 | | | |
| P | | | |
| parallels | 53 | | |
| perigee | 205 | | |
| photochemistry | 181 | | |
| photometry | 153 | | |
| photosphere | 17,20,24,46 | | |
| pipelines | 93 | | |
| planetary nebulous | 6 | | |
| plasma | 63 | | |
| – sheet | 74 | | |
| plasmaopause | 77 | | |
| plasmasphere | 77 | | |
| plumes | 38 | | |
| Pluto | 197 | | |
| polar | | | |
| – circles | 53 | | |
| – lights | 80 | | |
| precession of the equinoxes | 174 | | |
|
 | | | |
| prominence | | | |
| – active region | | 33 | |
| – quiescent | | 35 | |
| proton-proton cycle | | 138 | |
| proxy | | 45 | |
|
 | | | |
| Q | | | |
| quantity of movement | | 135 | |
| quiet sun | | 29 | |
|
 | | | |
| R | | | |
| radiation | | 114 | |
| radiative zone | | 11,13 | |
| radio waves | | 160 | |
| reconnection | | 72 | |
| reentry | | 110 | |
| reversal of the geomagnetic field | | 54 | |
| right ascension | | 206 | |
| ring current | | 76 | |
|
 | | | |
| S | | | |
| satellite orbits | | 103 | |
| Saturn | | 195 | |
| Schwabe cycle | | 29 | |
| shock wave | | 72 | |
| sidereal | | | |
| – rotation | | 9 | |
| – year | | 175 | |
| sievert | | 114 | |
| Single Event Unit | | 104 | |
| solar | | | |
| – activity | | 27,47,63 | |
| – atmosphere | | 24 | |
| – constant 1366.1 W m^{-2} | | 18,58 | |
| – corona | | 27 | |
| – day | | 176 | |
| – eruption | | 44 | |
| – flare | | 33,69 | |
| – spectrum | | 19 | |
| – system | | 49 | |
| – solar wind | | 20,22,38,47,69 | |
| solid core | | 54 | |

space	61	thermosphere	63
– debris	111	total electron content	101
– weather	93,121,125	trace	207
spicules	24	trans-horizon radar	120
spiral of Archimedes	21	tropical year	175
sprites	89	troposphere	58,59
stratopause	60		
stratosphere	60	U	
streamers	41	ultraviolet	60
sub-solar point	187	universal time	53
sub-storm	124	Uranus	195
Sun	46		
– composition	7	V	
– rotation	8	Van Allen belt	
sunspot cycle	47	– first	78
sunspots	27	– second	76
supergranules	15	Venus	191
synodic rotation	8	visible	161
T			
T Tauri	4	W	
tail	74	waves (telecommunications)	98
Terrella	80	Wolf index	30
terrestrial core	53		