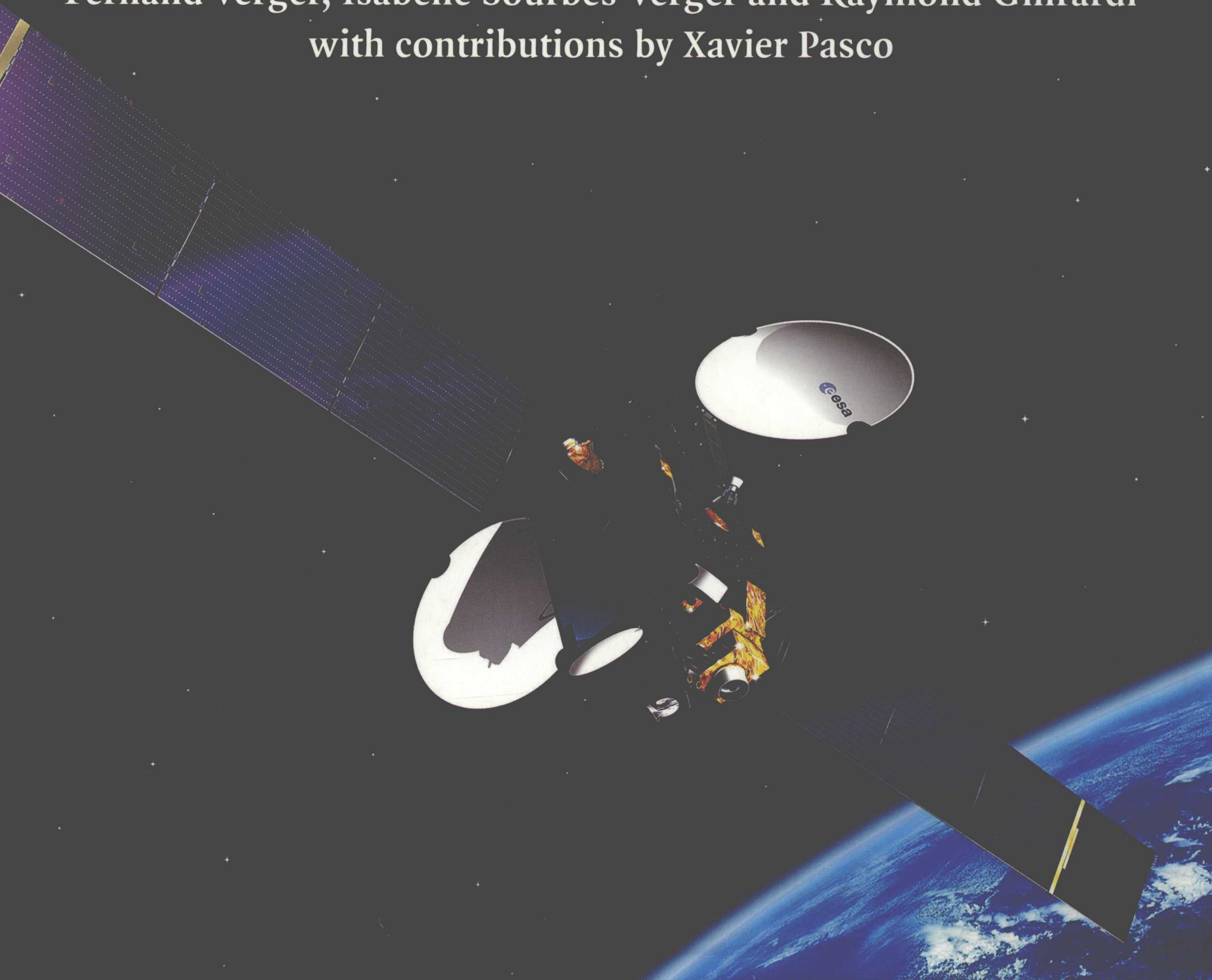
THE CAMBRIDGE
ENCYCLOPEDIA OF
SPACE
Missions, Applications and Exploration

Fernand Verger, Isabelle Sourbès-Verger and Raymond Ghirardi
with contributions by Xavier Pasco



The Cambridge Encyclopedia of

Space

Missions, *Applications* and Exploration

Fernand Verger,
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Foreword by **John M. Logsdon**

Translated by **Stephen Lyle** and **Paul Reilly**

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Foreword

This is an exciting volume, hard to put down. Its coverage is literally cosmic in scope. No area of space activity goes unexamined. The book's visualizations of various aspects of space activities and capabilities are unique, provide new perspectives on what actually goes on in the region beyond the atmosphere. Just to pick one example, Figure 4.3 is a remarkable achievement. It summarizes in one chart the whole history of space activity in a clear and immediately understandable fashion. To see the clustering of satellites in various Earth orbits, and then the relatively few space probes that have explored the Solar System away from Earth, charts the path of space development to date in a fashion that dramatically improves upon what can be communicated by words alone. There are many, many similar standout depictions of complex information throughout the volume.

Most of us who have spent long careers working in the space sector are wont to say 'space is just a place,' then ignore the implications of that reality as we discuss what happens in orbit and beyond. Not so Fernand Verger and his colleagues. Professor Verger is one of the most distinguished geographers in France, and his influence on this volume is evident. The *Cambridge Encyclopedia of Space* takes a geographical perspective whenever possible. It first of all describes outer space in physical terms, as an environment with its own natural characteristics that both facilitate and limit what can be done there. This unique perspective sets the stage for the rest of the work.

The first artificial Earth satellite went into orbit less than a half-century ago. This volume sets out in both words and images humanity's achievements, benefits, and aspirations since that historic step towards *homo sapiens* a space-faring species. It provides an understanding of the physical, economic, and political realities that must be taken into account as next steps are planned. It depicts the many uses that have already been made of the capability to put people and machines into space, and suggest next steps in space development.

As the volume discusses the building blocks of space activity – spaceports, launch vehicles, and various space missions themselves, its words are complemented throughout by innovative visual and graphical presentations and by well-chosen photographs. The text is of course an essential element of any encyclopedia, and the text here both provides comprehensive and reliable information and offers penetrating insights regarding the factors that shape activity in space. That said, it is its visual material that sets this volume apart from any previous attempts to capture in one place the complexity of space activity. Professor Verger and his associates have spent many years perfecting their depictions of space activity, and they have made a real contribution to our appreciation of how far we have come in opening up the space frontier, and to the increasingly global character of space exploration and exploitation. The *Cambridge Encyclopedia of Space* will be an essential reference work for every space professional and a boon for those just learning about this new arena for human activity.

John M. Logsdon
Director, Space Policy Institute
The George Washington University
Washington, DC, USA

Preface

Over the last forty years, circumterrestrial space has been gradually occupied as unmanned satellites have been put into orbit to carry out a range of different functions, and in a more limited way, as human beings have also increased their presence, annexing the closer regions of the cosmos to the inhabited world. It has hence become possible to build up a geography of space, and it is this idea that lies at the heart of the present work.

Designed along the lines of an explanatory atlas, this encyclopedia allows the reader to understand the extent to which space has been occupied and to follow the main motivations underlying its development. To begin with, it provides a cartographical view of this occupation, briefly specifying the conditions that prevail in the medium and the physical laws that hold sway over the use of circumterrestrial space. Many constraints must be faced in space development. These constraints explain the unequal distribution of satellites and probes gravitating in a number of different orbits, nearby or distant, circular or eccentric, equatorial, polar or other, depending on their mission, whether it be for exploration of our cosmic neighbourhood or further afield, civilian Earth observation, telecommunications, military surveillance, or human occupation.

However, space-based activities can also be considered in terms of their relationship to Earth. The successive passages of satellites criss-cross the whole surface of our planet, their tracks winding around it like the thread around a ball of wool. Satellites supply a new image of the globe and encourage links between different peoples. At the same time, the complexity of space technology creates a genuine hierarchy amongst the countries of the world, reasserting the traditional balance of power on Earth, yet introducing new features. The main steps in space conquest have led to the steady constitution of what appears today to be an exclusive club of space powers. However, the different activities have been mastered to quite varying degrees. Almost all countries around the planet now use space systems. Many are those who operate the satellites that only a much more restricted group of countries are able to put together. On the other hand, very few nations can provide their own launch capacity, and even fewer can claim to master the whole range of manned and unmanned, civilian and military space resources.

The present book aims to describe and account for space endeavour around the world and to provide a careful analysis of the policies that guide the great space powers. Apart from the chapter specifically devoted to space policy, the means of access and main areas of application are presented to show how the various programmes express different national preferences and their consequences for world affairs. The geopolitical aspect of the space phenomenon is indeed a key feature, since satellites procure for us a new vision of our planet and a clearer picture of its resources. Hence, remote sensing which is so important for cartographic applications raises the problem of how data should be made available, for it is as relevant to national independence and international security as it is to territorial development. In the same way, the flow of information, by telephone or television, for positioning or other purposes, provides the subject for a cartographic representation which illustrates the main areas of exchange, the weakened and transformed notion of border, and the appearance of ever sharper international features heavily dominated by the United States. Finally, the navigation programmes are closely linked to questions of strategic independence in a field where applications are still emergent.

Space activities thus have many repercussions and, on a global level, increase the weight of the dominant powers, whether they be military or civilian. These manifest themselves on an economic level through the development of new systems made possible by state-of-the-art technology and answer to a growing need to dominate the markets. Space bestows an undeniable advantage upon those that lay claim to it, not only by the information it offers, but also by the possibilities for direct intervention which it opens up. Finally, the occupation of space by human beings and projects to set up long-term space outposts lead to new prospects, although sensitive to the vacillation of political commitment.

Going beyond a simple description of the way current projects attempt to occupy space, this work aims to provide a conceptual basis for a genuine geography of space, without which it would be difficult to comprehend its development or the growing number of related issues in today's world.

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CHAPTER ONE

The *environment* of outer *space*

- DEEP SPACE
- NEAR SPACE

Deep space

In the Solar System distance measurements are commonly expressed in *astronomical units* (AU). One AU is the length of the semi-minor axis of the Earth's orbit, that is, 149 597 870 km. In the *distant universe*, which extends beyond the range of today's probes, they are expressed in light years (1 light year = 9.461×10^{12} km) or parsecs (1 parsec = 3.26 light years).

Deep space refers to the central part of the Solar System (fig. 1.1). This contains:

- one star, the *Sun*, of radius 696 000 km,
- the nine *principal planets* whose mean distances from the Sun, or mean heliocentric distances, vary between 0.39 AU for Mercury and 39.44 AU for Pluto (see table 1.1). The motion of the planets against the celestial sphere of fixed stars has been observed since the earliest times, earning them the name of wandering bodies (from the Greek πλανητης).

The planets are divided into two groups according to their physical properties. The *terrestrial planets*, Mercury, Venus, Earth and Mars, are relatively small, with a solid surface and an atmosphere. The *Jovian* or *giant planets*, Jupiter, Saturn, Uranus and Neptune, are distinctly larger and much less dense. Finally, Pluto falls into neither of these two families, being a small planet of low density.

The Solar System also includes:

- Natural satellites (moons) and rings orbiting certain planets (table 1.1).
- The *asteroids*, numbering several thousand, and grouped into families with orbits showing a wide range of eccentricities, sizes and inclinations to the ecliptic. The majority follow quasi-circular orbits at heliocentric distances between 2 and 3.5 AU, where they make up the main belt. Further out, the Hildas gravitate around 4 AU and the Trojans around 5 AU (see fig. 8.30).
- Several hundred other objects, similar to asteroids, which gravitate beyond the orbit of Neptune. These form the Kuiper Belt. Pluto and its moon Charon are now considered as members of this group.
- The *comets*, which have eccentric orbits, and primitive trajectories with semi-major axes measuring several tens of thousands of AU.

In addition, like the rest of the interplanetary medium, deep space is filled with:

- a flow of ionised particles originating in the Sun and known as the *solar wind*,
- *interplanetary dust*.

Certain parameters are used to locate positions of celestial bodies in the Solar System relative to Earth.

The *geocentric distance* depends on both the orbit of the celestial body and the orbit of Earth, and also on the position of these bodies on their orbits at the relevant time. Neglecting the different inclinations of the orbits relative to the ecliptic, it depends on the *phase angle*, that is, the angle between the planet, the Sun and Earth. At its maximum, the geocentric distance is close to the sum of one AU and one radius of the planetary orbit in question. This occurs at conjunction, in the configuration planet–Sun–Earth. Its minimum is close to the absolute value of the difference between one AU and the radius of the planetary orbit at opposition or inferior conjunction.

The *synodic period* is the time required for the system planet–Sun–Earth to come back to the same configuration as viewed from Earth. This period varies from 115.9 days in the case of Mercury, to 2 years 49.5 days for Mars. The synodic period marks the return of certain special conditions, such as a favourable configuration for sending out probes.

	Name	*Symbol*	*Equatorial diameter in km*	*Average density*	*Escape velocity in km / s*	*Synodic period*	*Heliocentric distance (AU)*	*Inclination on the ecliptic*	*Existence of satellites*	*Existence of rings*
terrestrial planets	Mercury	☿	4 878	5.44	4.25	115.9 days	0.387	7°00'		
	Venus	♀	12 104	5.25	10.36	1 year 218.7 days	0.723	3°24'		
	Earth	♁	12 756	5.52	11.18		1	0°	○	
	Mars	♂	6 794	3.94	5.02	2 years 49.5 days	1.524	1°51'	○	
giant planets	Jupiter	♃	142 800	1.31	59.64	1 year 33.6 days	5.203	1°19'	○	○
	Saturn	♄	120 660	0.69	35.41	1 year 12.8 days	9.555	2°30'	○	○
	Uranus	⛢	50 800	1.21	21.41	1 year 4.4 days	19.218	0°46'	○	○
	Neptune	♆	48 600	1.67	23.52	1 year 2.2 days	30.110	1°47'	○	○
	Pluto	♇	3 000	1 ?	?	1 year 1.5 days	39.439	17°10'	○	

Table 1.1. Planetary characteristics.

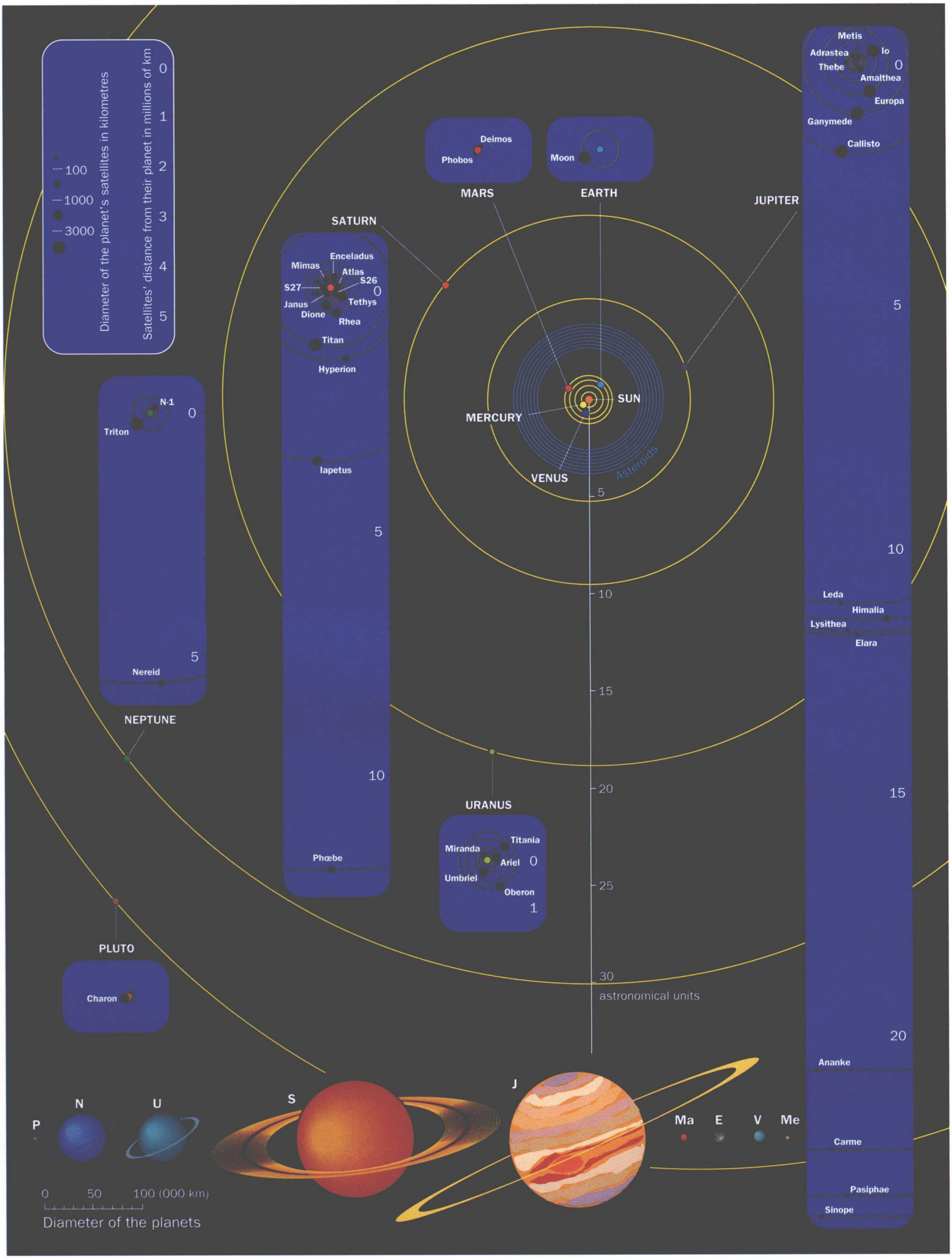


Figure 1.1. **The Solar System.**

Near space

The near space medium is dominated by the presence of a gaseous envelope, the *atmosphere*, held around Earth by gravity, and by the existence of a magnetic field, the *magnetosphere*, generated by the outer part of the terrestrial core.

Above the atmosphere, a plasma (ionised gas, composed of positively and negatively charged particles and ions) is trapped by the lines of force of the magnetosphere. This plasma constitutes the ionosphere and the various plasmatic regions of the magnetosphere.

The atmosphere

The atmosphere can be subdivided in different ways (fig. 1.2):

- By its composition, which remains constant in the lower convection zone or *homosphere*, up as far as the *homopause* (90 km). Ozone is most abundant between 40 and 50 km. Light elements predominate more and more in the *heterosphere* and, photoionised by solar ultraviolet radiation, give rise to the ionospheric plasma. Beyond the *exobase* (500 or 600 km), only the lightest atmospheric components remains (helium and hydrogen). These are liable to escape, although slowly, from Earth's gravitational attraction. This region is called the *exosphere*.
- By pressures and densities, which decrease more and more slowly with altitude. 50% of the mass of the atmosphere is located below 5 km, 90% below 16 km and 99.9% below 60 km. Even the most tenuous atmosphere exerts a braking effect on satellites, out as far as 600 km, thereby limiting their lifespans.
- By temperatures, which decrease with altitude by 5 °C to 10 °C per kilometre in the *troposphere* down to a first minimum in the *tropopause*. This is situated at 9 km altitude near the poles and about twice that near the equator. Aeroplanes fly mainly in the troposphere. Above the tropopause, temperatures increase with altitude under the effects of ozone dissociation by solar UV radiation, reaching 80 °C at around 50 km altitude, at the top of the *stratosphere*. This is called the *stratopause*. They then decrease to −70 °C in the *mesosphere*. Finally, beyond the *mesopause* (90 km), they increase rapidly in the *thermosphere* (which coincides

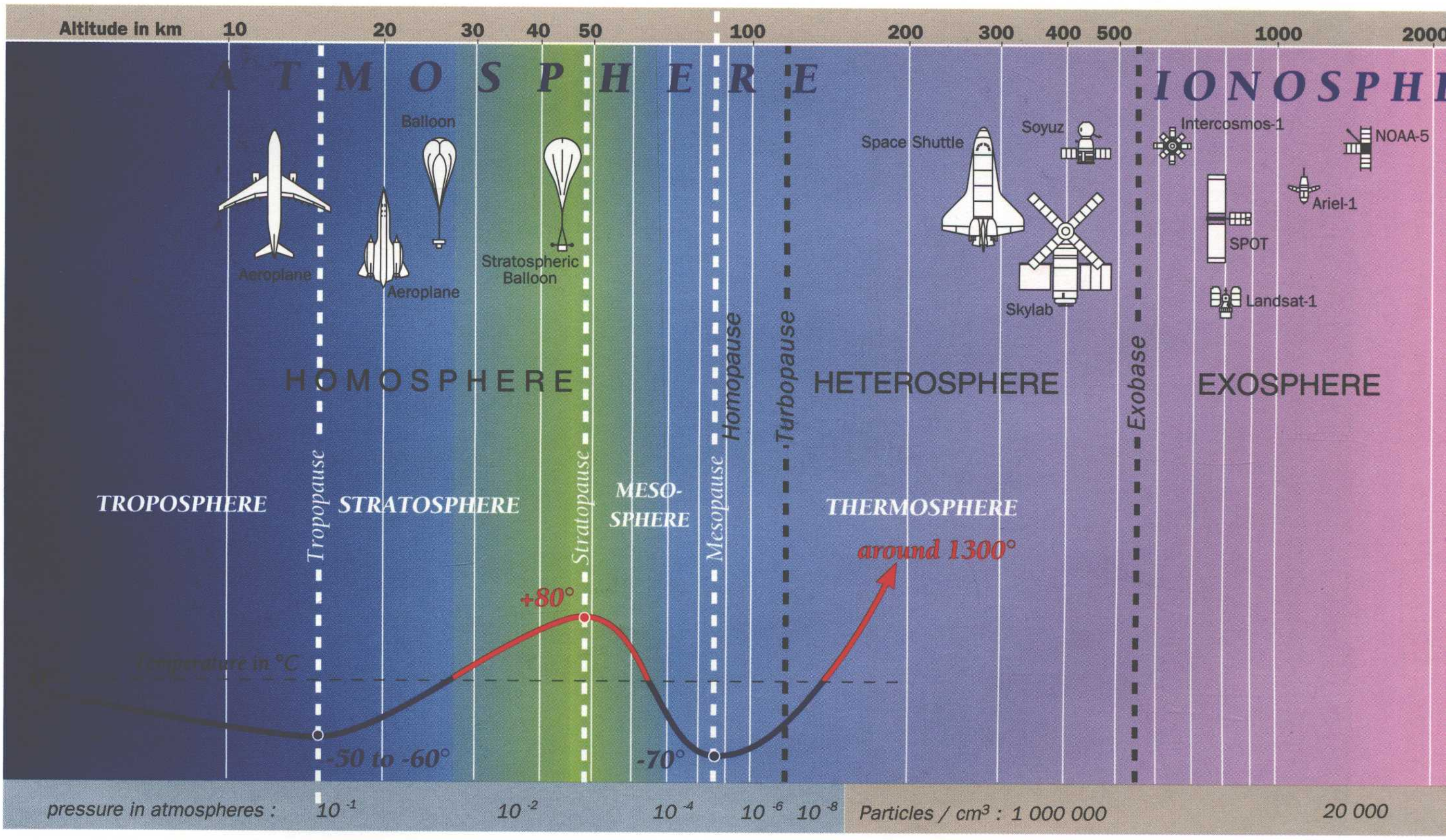


Figure 1.2. **Main divisions of near space showing airborne and space vehicles that visit them.**

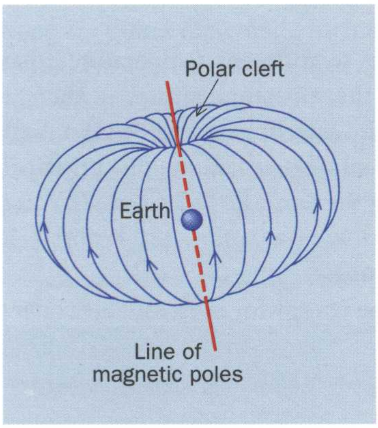


Figure 1.3. **Terrestrial magnetic field without the effects of the solar wind.**

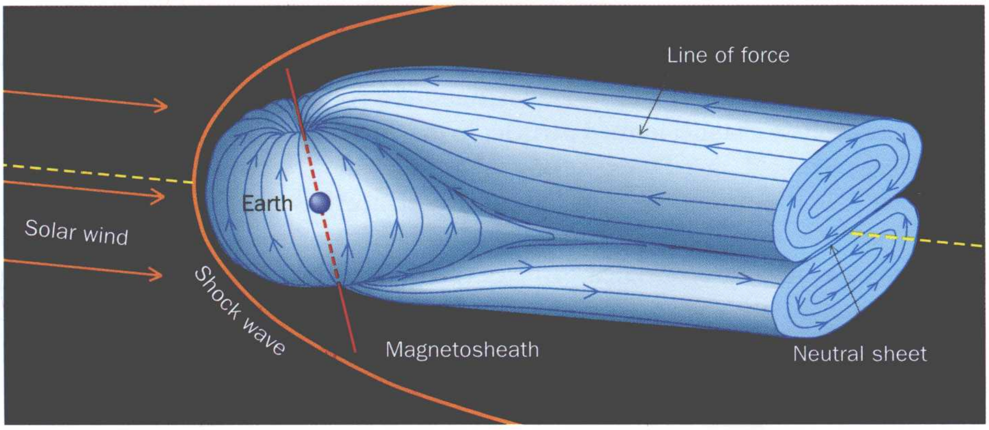


Figure 1.4. **Terrestrial magnetic field under the influence of the solar wind.** The magnetic field extends on the right, beyond the cross-section represented here to show the structure.

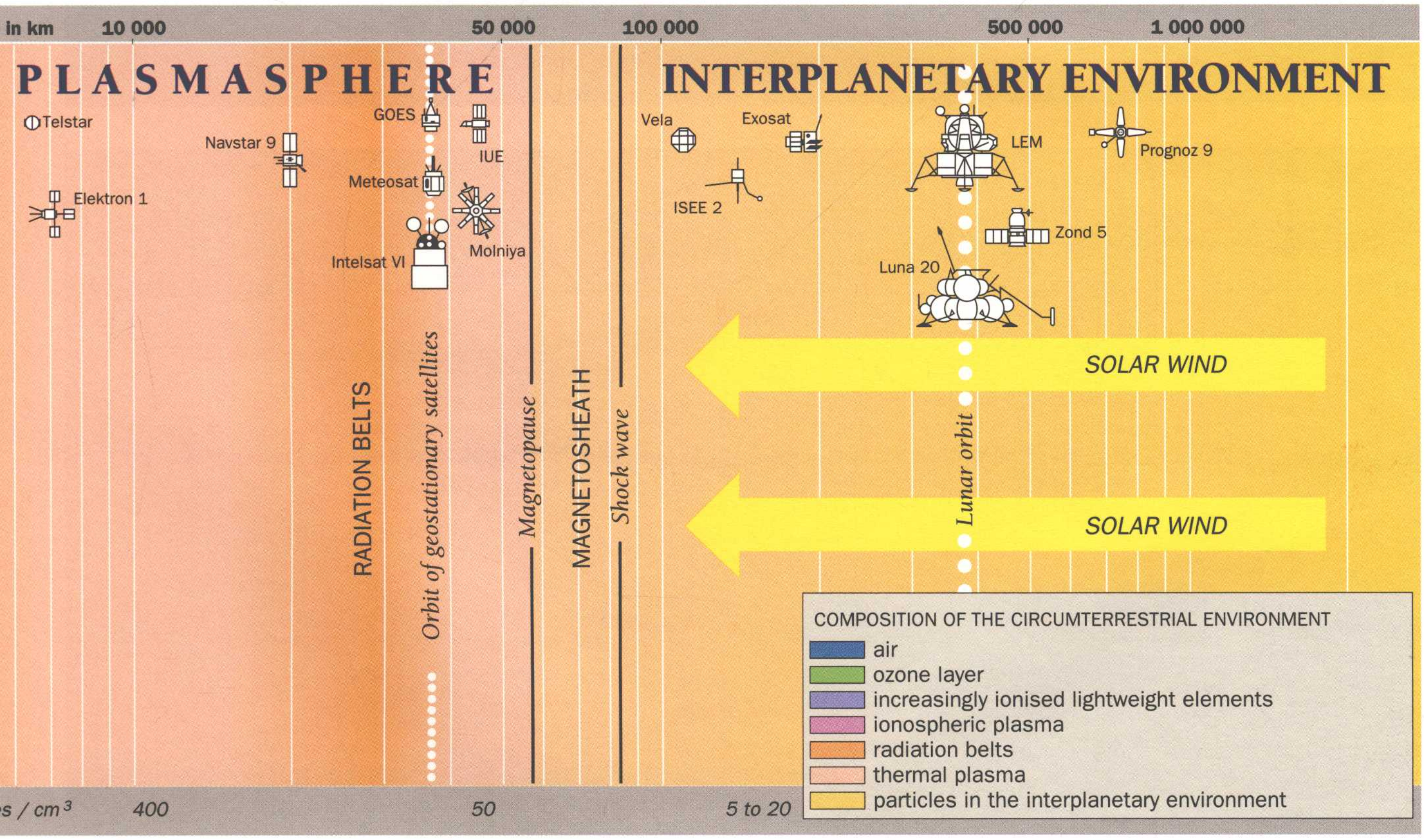
with the heterosphere) to reach the *exospheric temperature* of 1200 °C to 1300 °C, corresponding to the absorption of extreme UV solar radiation by photoionisation.

The magnetosphere

The magnetosphere forms a magnetic cavity in the solar wind, resulting from the interaction between the terrestrial dipolar magnetic field (fig. 1.3) and the interplanetary magnetic field 'frozen' into the solar wind (fig. 1.4). The surface on which the two fields balance is called the *magnetopause*. Beyond the magnetopause is a shock wave due to the supersonic flow of the solar wind. Between the two is the *magnetosheath*, where the magnetic field varies greatly in intensity and direction. This is dominated by particles from the interplanetary plasma (fig. 1.5).

Plasmas in the magnetosphere

The *ionosphere* begins in the outer thermosphere and is due to ionisation of the components of the terrestrial atmosphere carried to high altitude. This ionisation is caused by solar UV radiation and also by X-rays and primary cosmic radiation. Also to be found here are particles from the interplanetary plasma and



disintegration products from meteoritic and cometary grains in the upper atmosphere (source of metallic ions).

Above the terrestrial ionosphere proper, lines of force in the magnetosphere channel ionised particles in the direction of the magnetic field, thereby organising their distribution. The polar clefts represent the path of least resistance for charged particles to enter Earth's atmosphere. In periods of increased solar activity, accelerated particles (particularly in the magnetotail) are able to penetrate as far as the upper atmosphere along this route. There they excite atmospheric molecules, causing the polar auroras, borealis and australis.

Different zones can be distinguished in the magnetospheric plasma, in particular:

- The *Van Allen belts*, stable trapping zones in which particles (e.g., very high energy protons and electrons originating in cosmic rays, low energy electrons) bounce back and forth along the lines of force (taking between 0.1 and 2 seconds from one pole to the other, depending on the particle), whilst rotating about the Earth. Electrons complete this rotation in times from 1 to 10 hours in the sense of Earth's rotation, whilst protons move in the retrograde sense with a period of 5 seconds to 30 minutes. High energy protons are generally located between 2000 and 6000 km, but may fall much lower (down to 400 km) with the help of a magnetic anomaly between Brazil and South Africa. The radiation belts are filled with high energy particles which damage the silicon cells making up solar arrays, making them poor locations for satellites.
- The *plasmasphere* is made up of a very low energy plasma of the same composition and apparent origin as the ionospheric plasma, but at lower density (50 particles/cm^3).

Thermal conditions

Bodies in space are subject to different temperatures that depend less and less on the air temperature as the air becomes more rarified. In the mesosphere and beyond, heat exchanges are effected mainly by radiation, the principal sources in near space being the Sun (1200 kcal/m^2/h) and Earth (187 kcal/m^2/h by its own radiation, 430 kcal/m^2/h by reflection of solar radiation).

Solar radiation supplies the energy for most satellites operating in near space. In deep space, the greater the distance from the Sun, the lower the available energy and the more likely it becomes that other energy sources will be necessary, such as nuclear energy. Furthermore, the predominance of solar radiation in the thermal analysis of space vehicles means that, when there is no atmosphere, the surface exposed to the Sun heats to high temperature whilst the opposite surface cools by radiating into space. In order for satellites to function properly, it is important to establish a certain homogeneity of temperature (see table 1.2). One way of doing so is to use reflective cladding on the parts exposed to the Sun and absorbent cladding on the parts which need to be warmed up. During eclipses, in which the Earth prevents the satellite from receiving solar radiation, problems arise both from the reduction in radiation received and the thermal shock to which the various components of the satellite are exposed.

Dust and debris

Like the rest of interplanetary space, near space is filled with dust of cometary or other origins. Some of this dust may reach Earth's surface in the form of meteorites (the larger fragments) or micrometeorites (tiny fragments, less than 10 micrometres across). Fragments of intermediate dimen-

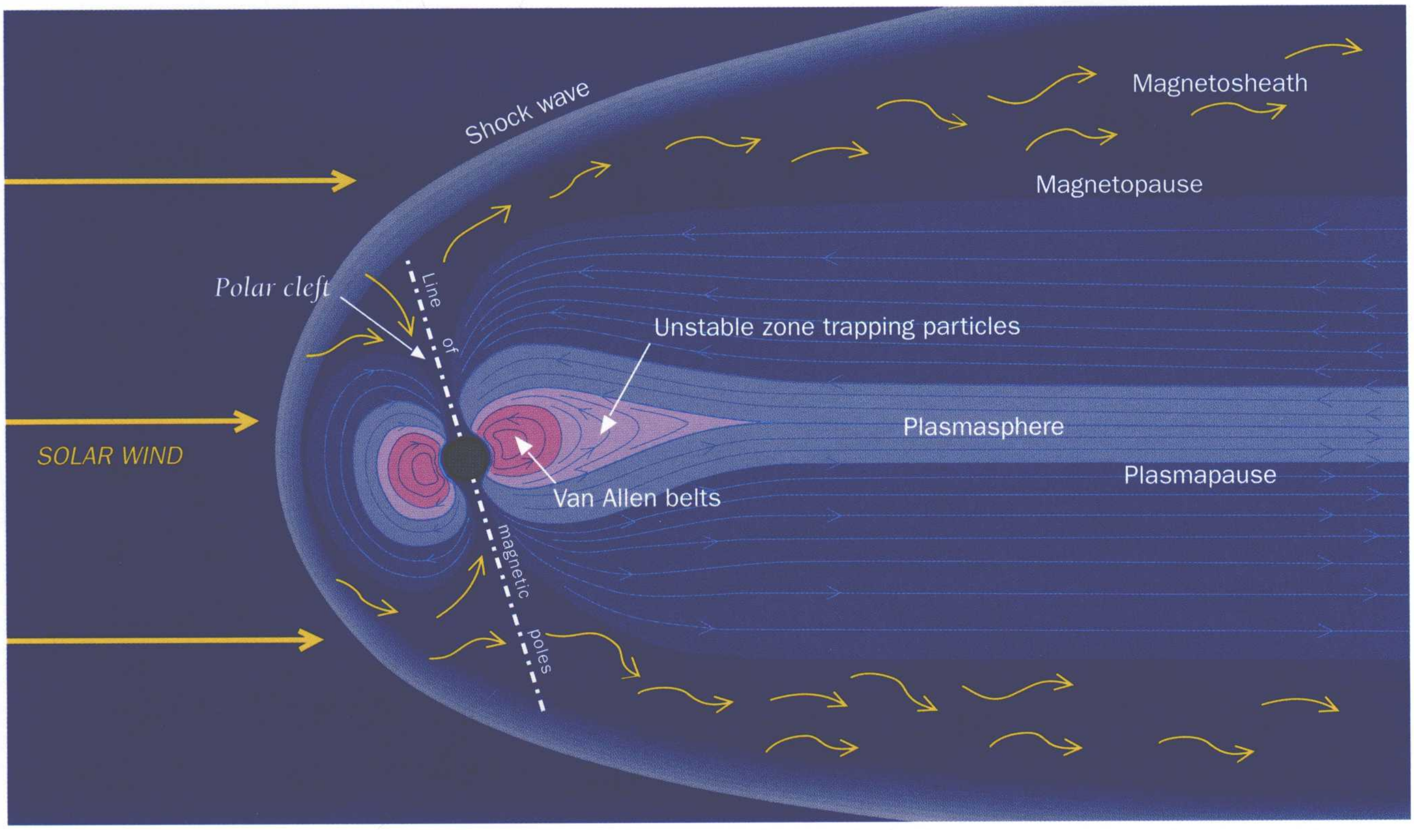
	DENSITY OF THE ATMOSPHERE	THERMAL EFFECT OF INFRARED RADIATION	ULTRAVIOLET RADIATION
POSITION	0 to 800 km	From 90 km ; stable from 500 km (inverse to the square of the distance from the Sun)	From 50 km stable at around 500 km
EFFECTS ON SATELLITES	Deceleration proportional to atmospheric density (=$1/2 \rho v^2$ x ballistic coefficient, ρ being the specific density, v the velocity). Negligible at 800 km, the loss of altitude is on the order of metres per revolution at 600 km, tens of metres at 400 km and hundreds of metres at 200 km. Overheating is linked with deceleration.	Flux of 1200 kcal/m^2 per h facing the Sun, none in the shade, variation of temperature on the order of +150 °C to −150 °C	Only affects certain sensitive materials (e.g. film)
EFFECTS ON HUMANS	Aeraemia at 5 000 m Anoxia at 15 000 m Boiling of body fluids at 19 000 m	Depend on the emissive power and reflectivity of module walls	Destruction of exposed tissue
COUNTER-MEASURES	Reacceleration; heat shield; pressurisation	Insulating materials; temperature exchangers; louvres, anti-infrared visors; air conditioning	Materials and visors containing filters

Table 1.2. **Environmental influences on space flights.**

sions are called meteors, which may disintegrate in the terrestrial atmosphere and be observed as shooting stars.

Near space is also cluttered with more and more debris from rocket launches, former satellites no longer in use, or satellites that have been destroyed. The disintegration of one satellite alone, Kosmos 1275, produced 242 detected fragments and millions of particles from the same source which are now moving through circumterrestrial space (see pages 54–56). Impacts from interplanetary dust and debris represent a real threat to satellites. Impact craters due to tiny particles have been observed on the Space Shuttle.

Figure 1.5. **Cross-section of the magnetosphere.** The Van Allen belts constitute a dangerous zone for satellites. Fortunately, the orbits of many Low Earth Orbit (LEO) satellites are located below them, whilst those of the Geostationary Earth Orbit (GEO) satellites lie well above them (from T. Encrenaz and J.-P. Bibring, 1987).



COSMIC RADIATION from solar eruptions	COSMIC GALACTIC RADIATION	RADIATION from the proton belt	METEORITES	WEIGHTLESSNESS
From 10 km, with maximum secondary cosmic radiation (the effect of primary cosmic radiation on air molecules) occurring between 10 and 15 km.		Between 2000 and 6000 km, with a max. at about 3000 km, drops to 400 km above southern Atlantic	Above the atmosphere	Not linked to altitude but to placing satellites in orbit
Increased braking through reheating/expansion of the upper atmosphere. Electrical breakdowns caused by magnetic storms created by solar eruptions. Destruction of cells on solar panels.	Destruction of solar panels		Impacts capable of unbalancing, damaging or destroying satellites	Mechanistic conditions under which gravity is not exerted (a favourable factor permitting the use of microgravity)
Severe irradiation (150 to 270 rads with protection of 2 g /cm^2). Eruptions (two or three a year) do not normally last longer than two hours.	Constant but weak irradiation, from 30 to 40 millirads per day	Irradiation varies with the altitude and as a function of the trajectory of the particles in relation to the space module (from 0.4 to 80 rads per day from 400 to 2400 km with protection of 2g /cm^2)		Circulatory troubles; joint troubles
Thickness and type of coating: but if the payload becomes too heavy it may be incompatible with current launch capacities.			Coatings and resistant shields	Artificial gravity produced by rotation is foreseen for future space stations

CHAPTER TWO

Orbits

- GENERAL PRINCIPLES
- THE ORBITS OF SUN-SYNCHRONOUS SATELLITE
- THE GEOSTATIONARY ORBIT
- THE LAGRANGIAN POINTS AND ASSOCIATED ORBITS
- ORBITS OF SPACE PROBE

General principles

Celestial mechanics and artificial satellites

The motion of natural and artificial satellites is governed by the law of universal gravitation. *Newton's law* can be stated as follows: two material points attract one another with a force proportional to each of their masses and inversely proportional to the square of the distance separating them. In symbolic form,

$$F = GM_1M_2/r^2$$

where G is the universal constant of gravitation and M_1, M_2 are the masses of the material points. The force on a satellite in orbit around Earth is equal to its mass multiplied by GM/r^2, where M is the mass of the Earth. Such a constant GM exists for any celestial body and for Earth has been accurately measured to be $\mu = 398\,603\ km^3/s^2$. This is known as the geocentric gravitational constant. *Kepler's laws* determine the characteristics of satellite orbits:

- The trajectory of a satellite in Earth orbit is an ellipse with one focus at the centre of the Earth (Fig. 2.1)
- The radius vector d joining the satellite to the centre of Earth sweeps out equal areas in equal times (Fig. 2.2).

At each point of the orbit, there is therefore a constant relationship between the speed *V* of the satellite, its distance from the centre of Earth and the angle γ between its direction of motion and the local horizontal (the plane perpendicular to the radius vector): $d.V.\cos\gamma$ is constant.

The product *dV* is the same at apogee and at perigee, since in both cases $\gamma = 0$ and $\cos\gamma = 1$. The shorter the radius at perigee, the greater the speed attained there (and conversely,

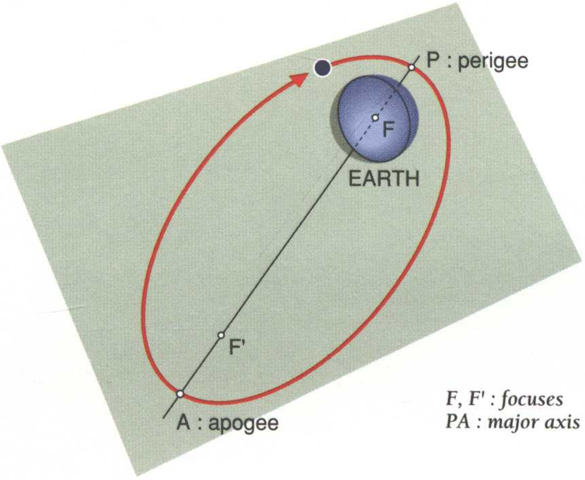


Figure 2.1. **Kepler's first law.** The case shown here is that of an artificial Earth satellite. The closest approach to Earth is called the perigee (P), and the furthest point the apogee (A).

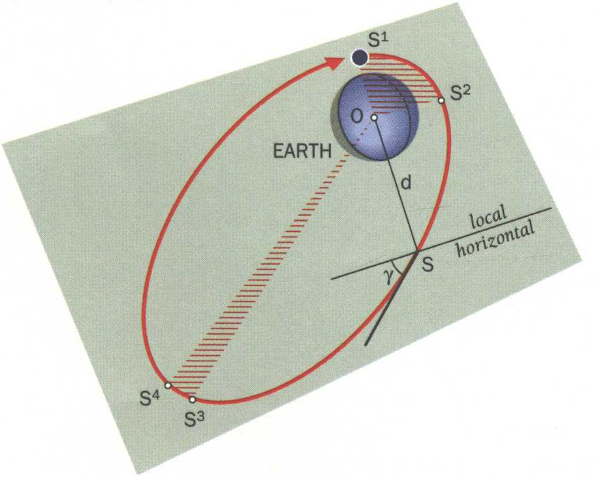


Figure 2.2. **Kepler's second law.** The two shaded areas are equal and the satellite takes the same time in going from S_1 to S_2 as it does in going from S_3 to S_4.

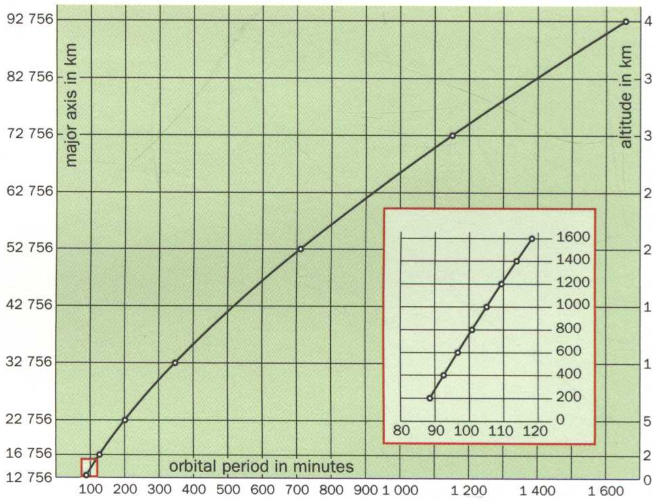


Figure 2.3. **Kepler's third law applied to Earth satellites.** Relation between major axis and period, detailed in the case of low orbits (inset).

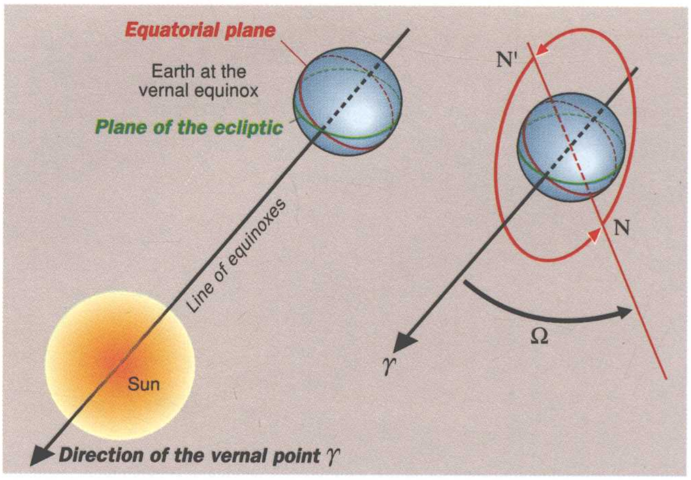


Figure 2.4. **Direction of the vernal equinox.**