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CHAPTER 1
A BRIEF PANORAMA

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1.1. THE MAGNETOSPHERE OF THE EARTH

The magnetosphere is the region of space within which the behaviour of plasma (i.e. ionized gas) is controlled by the Earth's magnetic field. The Earth's main dipole magnetic field is of internal origin, and decreases as the inverse third power of radial distance from the centre of the Earth. At ten Earth radii in the equatorial plane its intensity is a thousandth of its value at the Earth's surface. Electric currents due to the motion of charged particles in the geomagnetic field produce additional magnetic fields of comparable intensities. The global distributions of these magnetospheric current systems are described in Chapter 3. These magnetic fields add to the Earth's main dipole field illustrated in Fig.3.1a. The resultant pattern of the magnetic field lines has an extended tail in the direction opposite to the Sun (see Fig.3.1b). In the direction towards the Sun, field lines are "compressed" by a flow of solar plasma (ionized gas) blowing against the magnetosphere. The surface separating this solar wind flow from the magnetosphere is called the magnetopause. This boundary is shown in Fig.1.1, which also illustrates the tail-like shape of the magnetosphere. Since the solar wind plasma is supersonic, a bow-shock forms in front of the magnetopause. Across the bow-shock the solar wind plasma is decelerated and compressed. The region between the bow-shock and the magnetopause is called the magnetosheath.

Figure 1.1 also illustrates other typical regions inside the magnetosphere. Before proceeding with the description of magnetospheric plasmas and fields, the magnetospheric terminology shown in this illustration is explained. The entry layer just behind the frontside magnetopause is a region where solar wind plasma is directly captured by the magnetosphere. Some of the intruding solar wind particles spiral into the clefts (or dayside cusps) and eventually are precipitated into the atmosphere along high latitude geomagnetic field lines. Most of these charged particles are magnetically reflected without having been deflected from their helical trajectories (see Fig.1.2) by a fatal collision with any ambient atmospheric atom or ion. They escape along extended tail magnetic field lines. These magnetically reflected electrons and ions of solar wind origin form the plasma mantle adjacent to the tail magnetopause. Both the entry layer and the plasma mantle are part of the magnetospheric boundary layer which sometimes extends more than one Earth radius inside the magnetopause.

Another fraction of impulsively injected solar wind plasma particles drift longitudinally around the Earth; these replenish the plasmasheet region in the magnetotail near the

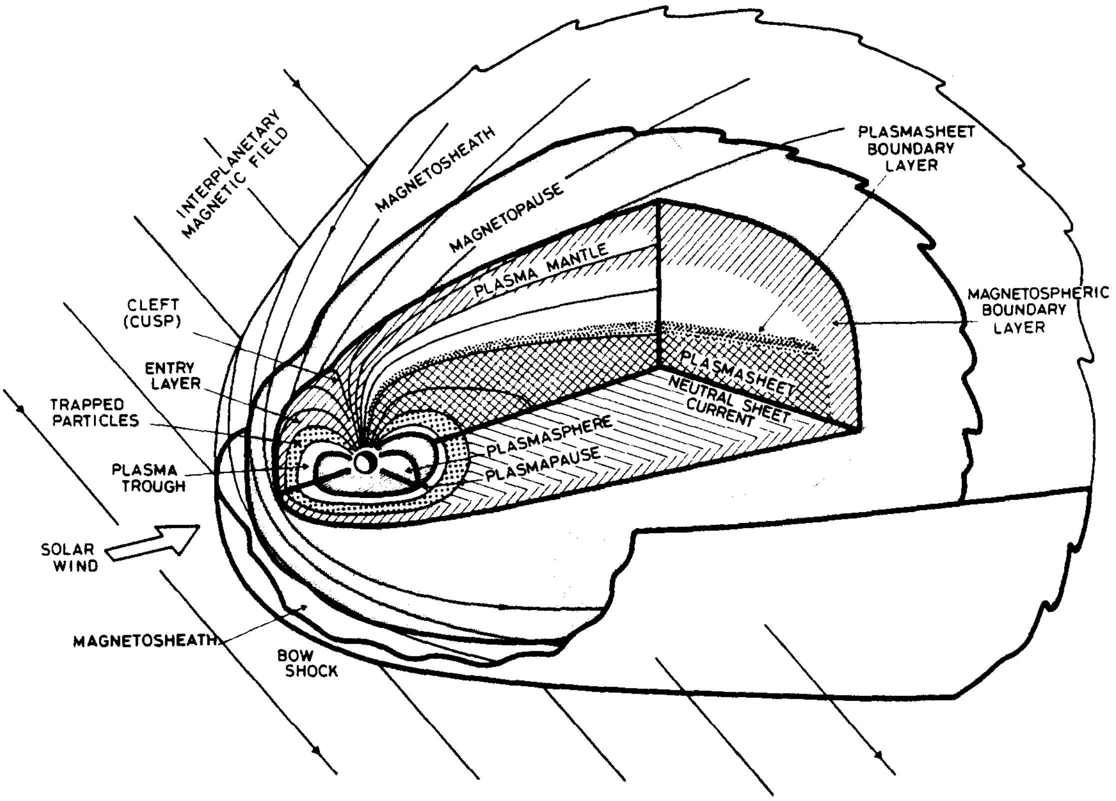

Fig.1.1. The "anatomy" of the Earth's magnetosphere. The Earth's magnetic field is not only a "trap" for charged particles (electrons and ions) but also a "shield" preventing solar wind plasma and cosmic ray particles having free access to the entire terrestrial atmosphere. Many physical processes operate within the many different regions of the magnetosphere. The terms are explained in the text.

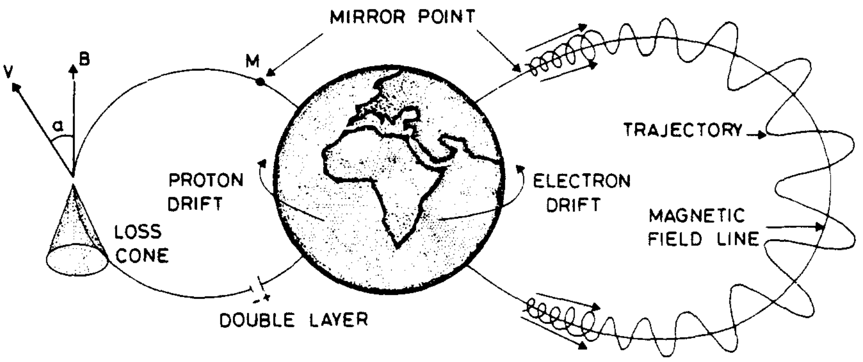

Fig.1.2. Trajectory of a trapped charged particle oscillating between two conjugate mirror points along geomagnetic field lines. Azimuthal, i.e. longitudinal, drifts of electrons and ions are due to magnetic as well as electric forces. When the pitch angle (α) of a particle is too small, i.e. is within the loss cone, the charged particle is not mirrored but it penetrates into the denser layer of the terrestrial atmosphere where it ionizes or excites neutral atoms. Localised field-aligned electric potential drops or "double layers" are sometimes present in the magnetosphere. The resulting parallel electric fields accelerate ionospheric ions upwards and magnetospheric electrons downwards; their mirror points are also reduced.

equatorial plane. At the separation between open magnetotail field lines and closed plasmasheet field lines, there is an intermediate region called the plasmasheet boundary layer,

Ions and electrons of high energies drifting in the geomagnetic field form an equatorial ring current. At the beginning of a geomagnetic storm, the flux of ring current particles is strongly enhanced. Geomagnetic storms are observed as a 1% decrease in the magnetic field intensity as measured at the surface of Earth.

The general characteristics of the hot plasmas, which are involved in auroral zone phenomena, are given in Chapter 7. When a 500 eV (electron volt) plasmasheet electron precipitates into the auroral atmosphere it is accelerated by an electric potential difference of 1 to 5 kV (kilovolt) distributed along the auroral magnetic field lines (see Fig.1.2). The pitch angle (α), between the velocity vector of the particle and the magnetic field direction, is significantly reduced as a result of the increase in the velocity parallel to the field. Consequently, the particle can plunge deeper into the denser layers of the terrestrial atmosphere. The probability of a collision with an ambient atom then becomes large. The atom that is hit is placed into an excited energy state; auroral light is emitted when the excited atoms revert to their ground state.

Besides these hot plasmasheet and ring current particles, the magnetosphere contains even higher energy electrons and protons. These particles, whose energy ranges from 100 kilo electron volts (100 keV = 10^5 eV) to more than 100 mega electron volts (100 MeV = 10^8 eV), form what is called the Van Allen radiation belts. The geomagnetic field constitutes, for these high energy particles, a "magnetic bottle" within which they can be trapped between two "mirror points" at opposite ends of a magnetic field line shown in Fig.1.2 for very long periods of time. It is this population of charged particles which was discovered by Van Allen in the early days of space research. The origin, the composition, the energy spectrum and the temporal variations of this trapped radiation are described in Chapter 8. This hard radiation constitutes a real hazard for manned flights; it is also damaging to spacecraft instrumentation as explained in Chapter 13.

Deep inside the magnetosphere at four to five Earth radii, there is another important region bounded by a nearly field-aligned surface which is called the plasmapause (see Fig.1.1). A rather sharp "knee" in the equatorial thermal plasma density determines the position of the plasmapause. The circum-terrestrial doughnut-shaped region bounded by the plasmapause is filled with low energy plasma (0 to 100 eV) originating in the ionosphere of the Earth. The velocity distribution of the electrons and ions trapped in this inner region of the magnetosphere, called the plasmasphere, is described in Chapter 6. The thermal and suprathermal charged particles trapped in the plasmasphere are produced in the upper atmosphere of the Earth by photoionisation and by ionising impacts of magnetospheric charged particles with atmospheric atoms. They form a comparatively cold plasma which diffuses upwards, mainly along magnetic field lines. Eventually these cold charged particles escape into the magnetosphere if their kinetic energies are large enough to overcome the gravitational and charge separation electrostatic potential energy. The plasmasphere is a large corotating reservoir filled with low energy plasma. During the day, when photoionisation by solar u.v. radiation increases the total ionisation content in the 100 to 300 km altitude range, new ionospheric plasma is pumped into the plasmasphere. However, during the local night-time hours, when recombination of free electrons and ions dominates at low altitudes, the trapped thermal plasma leaks out of the plasmaspheric reservoir. The resulting downward ionization flow helps to maintain a relatively high ionospheric density during the night time. The transfer of ionization between the ionosphere and plasmasphere results in a dynamical equilibrium coupling between the ionosphere and the magnetosphere.

During a magnetospheric substorm or a geomagnetic storm, this diurnal dynamical equilibrium is destroyed; then the plasmasphere is drastically disturbed, the sharp "knee" in the equatorial electron and ion density distribution is displaced toward the innermost magnetic field lines, and the equatorial distance of the plasmapause shrinks from five Earth radii (near local midnight) to less than three Earth radii during periods of severe geomagnetic activity. Although confirmed by direct satellite measurements, the discovery of the plasmapause boundary was made by Carpenter, in 1963, using ground-based whistler observations.

The distribution of charged particles in the magnetosphere, and their motions, are determined not only by the magnetic field (B), as shown in Fig. 1.2. for protons or electrons with energies larger than 100 keV, but also by the electric drift velocity, equal to E/B, which plays a key role in almost all magnetospheric plasma processes. The electric drift (or "convection" velocity) is perpendicular to both the electric field and the magnetic field vectors, E and B. It is therefore also essential to have available magnetospheric electric field models deduced empirically from observations. Unfortunately, reliable direct electric field measurements are difficult to make because of spacecraft charging and wake effects produced by the spacecraft itself. In Chapter 3 it is shown how the distribution of the electric field component perpendicular to the magnetic field direction can be deduced by other indirect methods.

It is now recognized that the magnetospheric electric field sometimes has a component parallel to the magnetic field. The double layer shown in Fig.1.2 and other parallel electric fields can play a decisive role in the acceleration of charged particles of ionospheric origin as well as those of magnetospheric or solar origin.

In addition to the d.c. electric and d.c. magnetic fields, a wide spectrum of a.c. field variations has been observed in the magnetosphere. Like charged particles, waves have been categorized according to their species or type, and to their energy or frequency. Micropulsations of the geomagnetic field of Ultra Low Frequencies (ULF) in the range of 3 millihertz (3 mHz) to 1 Hz are not only recorded on ground magnetograms; some of these magnetic pulsations (continuous Pc and irregular Pi waves) have now also been observed in the magnetosphere itself. The ULF waves are identified with propagating magnetohydrodynamic (MHD) Alfvèn waves and resonance oscillations of magnetospheric flux tubes.

At higher frequencies (a few kHz), there are whistler waves, guided along field-aligned plasma irregularities. The Very Low Frequency (VLF) waves can be produced either by lightning flashes in the troposphere or by plasma instabilities in the magnetosphere itself. In Chapter 5 the classification of all plasma waves presently observed in the magnetosphere of the Earth has been reviewed.

At even higher frequencies (100 kHz to 1 GHz) the magnetosphere is traversed by all sorts of electromagnetic radiation, either generated naturally by microphysical processes in the magnetospheric plasma, or produced on the ground by Man's activities.

1.2. THE INTERPLANETARY MEDIUM

In Fig.1.1, it can be seen that the magnetosphere is compressed in the sunward direction by a supersonic solar wind plasma flow. Its bulk speed, directed radially outward from the Sun, ranges from 200 km s^{-1} for quiet solar wind conditions to 800 km s^{-1} in high speed streams. The density of the solar wind electrons and ions varies from 2 to 20 particles per cubic centimetre (cm^{-3}). Protons (H^+) are the predominant ions. The next most abundant ion species are ionized Helium (He^{2+} or alpha particles), with 1 to 20% of the total number density, ionized oxygen (O^{7+}), and several other ions which are only minor constituents of the solar wind.

The electron temperature also varies over a wide range. The average electron temperature is of the order of 100,000 degrees Kelvin (10^5K). The average proton temperature is two or three times smaller, indicating the lack of energy equipartition among the charged particles in the solar wind at one Astronomical Unit (1 AU is the distance between the Sun and the Earth). As a consequence of the extremely low collision frequency between charged particles, their velocity distribution fails to be isotropic, (i.e. it is different in different directions) and sometimes it has two peaks characteristic of a plasma which is far from thermal equilibrium. Examples of highly non-Maxwellian and anisotropic velocity distributions are discussed in Chapter 9, devoted to the solar wind plasma.

From time to time, the Sun also emits bursts of protons in the MeV energy range. These energetic particles, called solar cosmic rays, can penetrate into the magnetosphere along polar cap magnetic field lines which are sometimes interconnected with the Interplanetary Magnetic Field (IMF). Their deep penetration into the polar cap atmosphere produces additional ionization which results in enhanced Polar Cap Absorption (PCA) of radio waves.

Galactic cosmic ray particles with an energy exceeding 1 GeV penetrate into the terrestial atmosphere through the magnetosphere. Their flux is modulated by the large-scale structure of the solar wind magnetic field in the heliosphere (i.e. the region around the Sun).

The IMF described in Chapter 10 is characterized by spiral magnetic field lines which are carried away from the solar photosphere far into the outer heliosphere by the radially expanding solar wind (see Fig.1.3). The polarity of the IMF is either predominantly positive (pointing away from the Sun) or negative (pointing toward the Sun), depending on the magnetic sector within which the field measurement is made. The alternation between sectors of opposed polarities has recently been explained by the presence of a current sheet corotating with the Sun and undulating in heliographic longitude. As for the neutral sheet in the magnetotail of the Earth, the magnetic field direction seen above this heliospheric neutral sheet is opposite in direction to that measured aboard a spacecraft located below.

If magnetic field lines could be traced in the solar wind, all sorts of irregular structures and small scale inhomogeneities would be observed superimposed on the idealized Archimedean spiral lines which are generally drawn to represent the IMF distribution. Indeed, hydromagnetic waves and turbulence, shock waves and thin current sheets produce a wide variety of directional discontinuities in the interplanetary magnetic field distribution (see Chapter 10).

The solar wind plasma and magnetic field interact with the geomagnetic field forming the bow shock and the magnetopause. Any time variations or small scale inhomogeneities in the solar

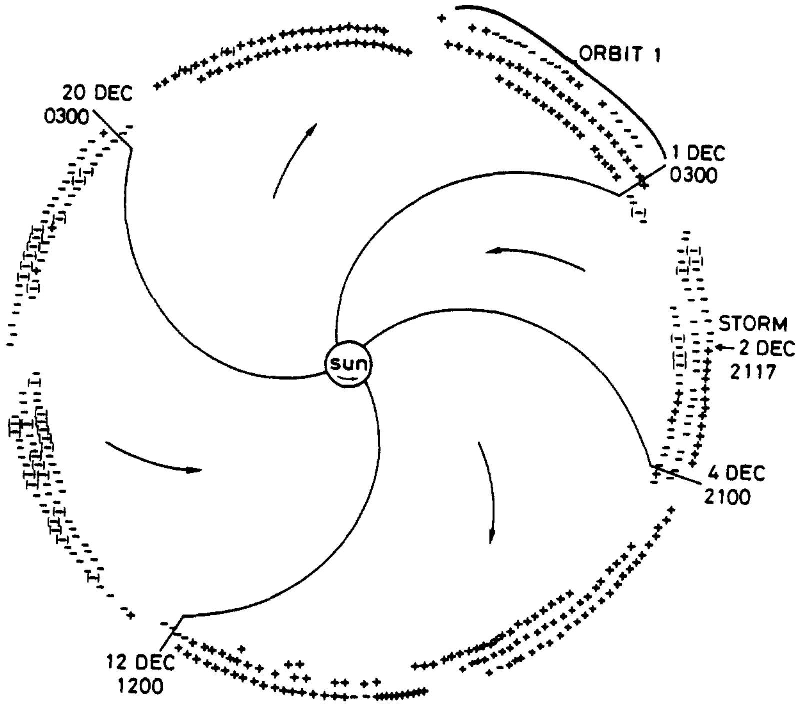

Fig.1.3. The sector structure of the interplanetary magnetic field. The magnetic field lines are nearly parallel to the solar equatorial plane and have an Archimedean spiral shape. The direction of the magnetic field is either away from (+) or towards (-) the Sun depending on whether the measurement is made above or below an undulating current sheet separating interplanetary magnetic field lines connected to solar regions with opposite magnetic polarities. Measurements made in December 1964 are shown.

wind flow produce a perturbation in the geomagnetic field which is felt even at the surface of Earth. Solar wind variations sometimes have drastic consequences for the magnetosphere, as well as for the Earth's upper atmosphere which is linked to the magnetosphere through the ionosphere. How much this affects the lower atmosphere, weather and climate is an open question, as indicated in Chapter 13. Other consequences of solar wind and magnetospheric processes on Man's environment and Man's technical devices (e.g. telecommunication systems, power lines, pipelines, spacecraft instrumentation, etc.) are also discussed in Chapter 13.

Therefore it is interesting to develop and to follow progress in solar-terrestrial relationships and in magnetospheric physics, not only from a purely academic point of view; indeed these fields should be investigated in future bearing in mind the consequences that they may have for weather and climate. But even more importantly, solar-terrestrial relationships will become essential for Man's future experimental activities, and eventually for his industrial activities, in orbit around the Earth and on the Moon.

1.3. MAGNETOSPHERES OF OTHER PLANETS

In his quest for new knowledge, Man has started exploring the Planets of the solar system. Plasmas and fields have been found around all the planets already visited. Magnetospheres somewhat like that of the Earth have been discovered around Jupiter, Mercury and Saturn.

However, a closer look shows that all the planetary magnetospheres are quite different from each other. As for most other bodies in Nature, each individual planet is a "special case" with its own characteristics.

For instance, Jupiter has a very large magnetosphere. While the magnetopause of the Earth is at 10 Earth radii $\underline{R_E}$ (approx. 63,700 km), in the sunward direction, the magnetopause of Jupiter is 100 Jovian radii $\underline{R_J}$ (7,000,000 km) from Jupiter in the sunward direction. Because of the high spin velocity of Jupiter and the presumed large conductivity of its atmosphere, its huge magnetosphere co-rotates with the planet. The spin period is only 10 hours. A natural Jovian satellite (Io) is the primary source of charged particles trapped in the Jovian radiation belts. Indeed, sulphur dioxide molecules (SO_2) on Io's surface are sputtered off Jupiter's moon along far reaching ballistic orbits. These escaping particles are then broken up and ionized by additional particle bombardment. Consequently, a relatively large and dense plasma torus, consisting primarily of sulphur and oxygen ions, is formed along the orbit of Io. All this is explained in more detail in Chapter 11 where, in addition, a pulsar-like mechanism is suggested to explain the long known radio-emission from Jupiter and its 10-hour periodicity.

Most recently Saturn has also been visited by Pioneer 11. The magnetic moment of the magnetosphere of Saturn is 530 times larger than the Earth's dipole moment, and is almost parallel to the rotation axis of Saturn. By contrast for the Earth the rotation axis and magnetic moment are almost in opposite directions. The magnetopause of Saturn is at 7.5 $\underline{R_S}$ (450,000 km) in the sunward direction. The relatively few and preliminary results which are available concerning the plasma trapped in the magnetosphere of Saturn have also been reported in Chapter 12.

Mercury has a much smaller magnetosphere than does the Earth. The subsolar point of the magnetopause of Mercury is at a planetocentric distance of only 1.36 $\underline{R_M}$ (3,220 km). Its magnetic moment is 1/3400 of the Earth's dipole moment. In Chapter 12 a model fitting the observed magnetic field distribution of Mercury is shown.

Although Venus has no significant magnetic field and is devoid of a magnetosphere, plasmas and fields have been observed in its vicinity. Instead of a magnetopause, an *ionopause* is formed by the interaction between the solar wind flow and the unshielded atmosphere of Venus. But, as in the case of the other planets, a bow shock is formed in front of the Venusian ionopause. The situation is less clear for Mars, where the magnetic field is probably not strong enough to prevent the solar wind from reaching the upper layers of the Martian atmosphere.

1.4. PERSPECTIVES AND FUTURE PROJECTS

Although necessarily incomplete, this brief panorama of the *current state* of our knowledge about "solar system plasmas and fields" indicates how many pieces in the jig-saw have already been assembled in the 25 years since the first successful launch of an artificial satellite. From experiences with older but still expanding fields of research and of modern technology, space research is still in its early phases and far from any saturation level.

The perspectives described in Chapter 14 are promising. Thanks to the great efforts being made, space technology is improving in all directions, such as aiming to make space experimentation less expensive and more flexible with the space shuttle, increasing the time resolution and the precision of *in-situ* instrumental techniques, increasing the performances of the telecommand systems, of on-board data processing, and of data transmission systems, etc. All these will necessarily serve to enhance the return expected from space research and, more broadly, from all Man's space activities.

Several space exploration projects are presently in operation in the solar system (Pioneers-10 and -11, Voyagers-1 and -2) and in relation to the Earth's magnetosphere (GEOS-2 and ISEE-1,-2 and -3, among the most important scientific and civilian projects). Several ambitious projects are in preparation. The International Solar Polar Mission (ISPM) is a joint NASA-ESA project to explore the heliosphere beyond the ecliptic plane. The Galileo project is to explore the magnetosphere of Jupiter with a satellite orbiting around the biggest planet of our Solar System. Even a "rendez-vous" with a periodic comet (Halley) is planned for 1986. The upper atmosphere of the Earth and its magnetosphere will be carefully reexamined within the framework of the Spacelab programme as well as with the different spacecraft planned for the "Origin of Plasmas in the Earth's Neighbourhood" (OPEN) project.

Not only do spacecraft launches and instrumentation improve rapidly, but so also do data analysis systems. This also raises promising perspectives for the groups of interdisciplinary scientists who analyse and interpret the overwhelming amount of experimental observations. The tools are ready and improving every day. Are there enough qualified workers available to use these tools and the information?