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CHAPTER 12

THE MAGNETOSPHERES OF SATURN, MERCURY, VENUS AND MARS

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12.1. THE MAGNETOSPHERE OF SATURN

On 1 September 1979, the Pioneer-11 spacecraft discovered and penetrated the magnetosphere of Saturn. Saturn is the second largest planet in the solar system. Its radius is 60,000 ± 500 km, with a polar flattening of about 5280 km. It has a density of about 0.7 g cm^{-3}. The planet rotates with a period of 10 hr and 14 min, and it revolves around the Sun with a period of 29.46 years. Pioneer Saturn made photometric and polarization measurements of four of Saturn's moons (Iapetus, Rhea, Dione, and Tethys), and passed within 356,000 km of Titan. It may also have discovered a previously unknown moon of Saturn. Earth's moon is well outside the terrestrial magnetosphere and has no effect on it. However, many of Saturn's moons are inside the zone of trapped radiation and interact strongly with the trapped particles.

Before the Pioneer encounter, five rings of Saturn had been tentatively identified. From the planet outward, they are the D-, C-, B-, A- and E-rings. The spacecraft discovered two new Saturnian rings. One of these, called the F-ring, lies just outside the A-ring. The gap between the F-ring and the A-ring has been tentatively designated the Pioneer division. The other new ring has been called the G-ring, and it lies well outside the F-ring.

The planetary magnetic field of Saturn has an equatorial value of 0.2 G, corresponding to a magnetic moment of 4.3×10^{28} G cm^3, which is 530 times larger than the dipole moment of the Earth. The polarity of the field is opposite to that of the Earth. The field is largely dipolar. It has a surprisingly high degree of axial symmetry : the dipole axis of the field is tilted less than 1° from the rotational axis of Saturn. An offset of the magnetic centre from the centre of Saturn is no more than 0.04 $\underline{R}_S$, principally in the polar direction.

The magnetic field of Saturn has created a magnetosphere intermediate in size between the magnetospheres of Earth and Jupiter, with trapped particle intensities comparable with the Earth's. Saturn has a detached bow shock wave and a magnetopause quite similar to those of the Earth. The overall form of the magnetosphere is simple and compact. The size of Saturn's magnetosphere is very responsive to changes in the solar wind dynamic pressure.

The outer magnetosphere, out to the magnetopause at 7.5 $\underline{R}_S$, contains lower energy plasma, its flow appears to be consistent with co-rotation with Saturn's magnetic field. The ion species measured in this region preclude the solar wind or the Saturn ionosphere as being the main source of Saturn's magnetospheric plasma. The tentative identification of O^+ and OH^+ as the dominant ions indicates that the low-energy particles are probably produced by dissociation of the ice on Saturn's rings or moons. The fluxes of trapped particles in the outer magnetosphere and their angular distributions are strongly influenced by the time-varying solar wind.

Rings of particulate material, and several small moons near the rings, strongly affect Saturn's trapped radiation. The outer atmosphere is terminated sharply by a sudden drop in both the proton and electron fluxes in a region between 6.5 and 4 $\underline{R}_S$. This reduction in particle flux is attributable to effective particle absorption by Dione, Tethys, Enceladus and the E-ring.

The inner region, inside 4 $\underline{R}_S$, contains higher energy particles, the particle fluxes and energies increase inwards and the spectra become much harder and more complex. Particle absorption features near 2.5 $\underline{R}_S$ and the imaging photopolarimeter have indicated the existence of a small Saturn moon with a diameter of about 200 km.

Inside 2.3 $\underline{R}_S$, the outer edge of the A-ring, there is a sharp cut off of all trapped particles. A nearly complete absence of radiation belt particles on magnetic flux tubes intercepted by the Saturn rings leaves a shielded region close to the planet. This shielding prevents the further build up of electron intensities at lower altitudes, which otherwise would have been present and would have made Saturn a strong radio source observable from the Earth.

The radio occultation observations of Saturn indicate that Saturn has an ionosphere composed of ionized atomic hydrogen with a temperature of about 1250 K in its upper regions. The ionosphere has two peaks in electron density; the highest is 9.4×10^3 cm^{-3} at 2800 km, and the second is 7×10^3 cm^{-3} at 2200 km.

After its encounter with Saturn, Pioneer Saturn headed out of the solar system, travelling in the direction in which the solar system moves with respect to the local stars in the galaxy. Other spacecraft are following along the trail blazed by Pioneer Saturn. Voyager-1 passed by Jupiter in March 1979 and reached Saturn in November 1980. Voyager-2 has also passed beyond Jupiter and encountered Saturn in August 1981, with hopes of travelling on to an encounter with Uranus in 1986.

12.2. MERCURY'S MAGNETOSPHERE

So little was known of Mercury before the historical voyage of Mariner-10 that the mission was virtually Man's first look at the innermost planet of the solar system. Mariner 10 made three close fly-bys of the planet on 29 March and 21 September, 1974, and on 16 March, 1975. On its first encounter with Mercury, Mariner-10 unexpectedly discovered a global, intrinsic magnetic field and the modest sized magnetosphere of Mercury.

The trajectory of the first fly-by was on the darkside, near the equator, with a closest approach distance from the surface of 703 km. The second encounter was targeted so as to optimize imaging coverage of the South polar regions and passed too far from Mercury (50,000 km) to provide any direct observation of its magnetosphere. The third encounter was similar to the first, being a very close approach towards the dark side, but was carefully modified to pass near the North polar region at a distance from the surface of only 327 km.

The observational data of Mercury's magnetosphere were obtained by three scientific instruments on Mariner-10, a magnetometer, a plasma spectrometer and a charged particle telescope. Mercury, the smallest of the planets except possibly Pluto, has an equatorial radius of 2439 km (versus 6378 km for Earth). It has a detached bow shock wave, a magnetopause and a tail current sheet quite similar to those of Earth. The magnetopause crossing data indicate that the size of Mercury's magnetosphere is very small (see Fig.12.1).

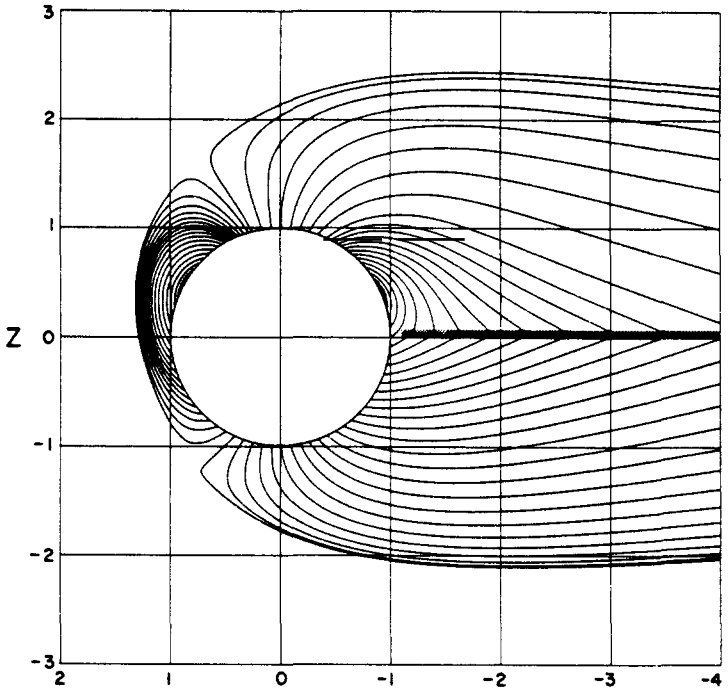

Fig.12.1. Mercury's magnetospheric magnetic field lines of in the noon-midnight meridian plane calculated from a model study of observational data obtained by Mariner-10. Field lines are tangential to the magnetopause at the boundary. The X-axis is directed from Mercury to the Sun, and the Z-axis is normal to the orbital plane of Mercury and directed Northwards.

Mercury itself occupies a much larger fraction of its magnetosphere than does Earth. There is no evidence for the permanent existence of a trapped charged particle radiation belt.

The observational data from Mariner-10 have been used to carry out quantitative studies of Mercury's magnetosphere. Determining the characteristics of the intrinsic planetary magnetic field is difficult because the magnetospheric magnetic field of Mercury includes a substantial contribution attributable to external field sources. Even at closest approach to the planet, the magnetic field observations were made in regions which are not very distant from the effects of the electric currents which flow in the magnetopause and the tail current sheet. Therefore, a proper representation of the external field becomes very important for the success of a quantitative model for the magnetosphere of Mercury. The most recent result is a three-dimensional model magnetosphere which includes a tail current sheet and the confinement of all planetary field lines within a modest sized magnetosphere. Figure 12.1 shows the field lines and the tail current sheet of the three-dimensional model in the noon-midnight meridian plane. The size of the magnetosphere agrees well with the magnetopause crossings directly observed from Mariner-10.

The model, based on all magnetic field data from Mariner-10, concludes that the planet has a dipole moment of 2.4×10^{22} G cm^3, which is 1/3400 that of the Earth's dipole moment, tilted 2.3° from the normal to the planetary orbital plane. Its polarity is identical to the Earth's. However, the planetary intrinsic field of Mercury is very much distorted from that of a simple centred dipole. The quadrupole and octopole components of the planetary magnetic field are quite significant in magnitude as compared with its dipole. The existence of a quadrupole field indicates an axial offset of the planetary magnetic centre by a distance of $\sim 0.2\ \underline{R}_M$ Northward from the planetary gravitational centre. This causes the asymmetry of the planetary intrinsic field and of the magnetospheric magnetic field about the orbital plane of Mercury. The surface intensity of the axial octupole field of Mercury is about 29% of that of the dipole field. The presence of a relatively large octupole moment indicates that the average radius of the source current system inside the planet is a significant fraction of the planetary radius. This is consistent with present understanding of the internal structure of Mercury, namely that the planet has a large dense solid core with a radius which is about three quarters of the planetary radius.

Results from the first encounter of Mariner-10 indicate that the magnitude of the magnetospheric magnetic field at the stagnation point of the solar wind flow is about 160 nT, and that the planetocentric distance to the magnetopause at the stagnation point is $1.32\ \underline{R}_M$. The stagnation distance may change by $\pm$ 10% due to the varying dynamic pressure of the solar wind. Across the tail current sheet, the magnetospheric magnetic field undergoes a sharp change of 80nT in the field component parallel to the Mercury-Sun line.

The magnetosphere of Mercury may be divided into two regions, a region of open field lines, where all field lines are connected with the tail and its current sheet, and a region of closed field lines. No observations of the latter region were made by Mariner-10.

The interior plasma features in the magnetosphere of Mercury compare well with those of the Earth's magnetosphere. Along the field lines connected with the polar cap region of Mercury, the flux of observed low energy electrons was very small. Hot electrons in the keV range were observed along the field lines connected with the inner edge of the tail current sheet. The remainder of the open field-lines region was observed to have electrons of energy 100 to 200 eV. Observations by the charged particle telescope showed intense transient bursts of energetic electrons along field lines connected with the inner edge of the tail current sheet. This indicates that a local acceleration process must be active in the magnetospheric tail.

The external magnetic field, which represents a significant fraction of the magnetospheric magnetic field of Mercury, is induced by electric currents flowing in the tail current sheet and the magnetopause. The location of the two source surfaces and the intensity of the source currents vary all the time in response to the time-varying conditions of the solar wind. As a result, the solar wind conditions produce a direct temporal effect on the magnetospheric magnetic field of Mercury. In the region where the gradient of the external field is large, relatively large fluctuations in the magnetic field were observed by Mariner-10.

12.3. MAGNETOSPHERES OF VENUS AND MARS

Contrary to the planets described previously, neither Mars nor Venus has an intrinsic magnetic field, although each has a well-developed ionized gas envelope (ionosphere). This is why the ionized cavity surrounding each of these planets is sometimes called a pseudo-magnetosphere.

The usage of this term can be avoided if the definition of a magnetosphere is extended to be the limited region of space where the presence of the planet perturbs the direction and changes the value of the interplanetary magnetic field downstream of the bow shock. Such a general definition is then applicable to all known planets, even those without an intrinsic magnetic field.

Since the number of spacecraft studying the magnetospheres of the other planets is much less than those studying the Earth's magnetosphere, it is clear that there remain many unsolved problems in the physics of non-terrestrial magnetospheres. Studies of the magnetosphere of Venus are now at a stage comparable with studies of the Earth's magnetosphere 15 years ago. Knowledge of the Martian magnetosphere is at an even earlier stage.

12.3.1. Magnetosphere of Venus

Magnetic field and plasma measurements near Venus were carried out for the first time by Venera-4 on 17 October 1967, at a height of 200 km above the surface of the planet; Mariner-5 approached the planet the next day at a minimal distance of 300 km, while Mariner-10 passed at a distance of several thousands of km. Venera-9 and -10 explored Venus in 1975-76, and Pioneer Venus Orbiter has since the beginning of 1978.

The first magnetic field measurements were carried out by Dolginov and his colleagues, with Venera-4. Their results showed that the intrinsic magnetic field of Venus is weak, not more than 10^{-4} G (10 nT) at the surface of the planet, and that it cannot create an obstacle for the solar wind as the geomagnetic field does. These early results were confirmed by Mariner-5 and -10, as well as by later probes orbiting around Venus.

The solar wind interacting with the ionosphere of Venus forms a bow shock which is relatively much closer to the planet than in the case of the Earth. This difference arises from the fact that the obstacle creating the bow shock is not the intrinsic magnetic field of Venus but the small magnetic field produced by currents induced in the ionosphere by the solar wind flow itself. The interplanetary magnetic field moving with the solar wind plasma cannot penetrate into the electrically conducting ionosphere and "accumulates" in front of the planet, forming a magnetic barrier (magnetic obstacle) to the solar wind.

A typical vertical electron density profile observed in the day-side ionosphere of Venus is shown in Fig.12.2. The sharp upper boundary where the electron density decreases rapidly at a height of 260 km is called the ionopause. This is a typical feature of the ionosphere of Venus which was observed both by American and Soviet spacecraft. Until 1979, it was generally believed that the shielding electric currents producing the magnetic obstacle were distributed throughout the day-side ionosphere of Venus. However, from the magnetic field measurements of Pioneer Venus Orbiter, Russell and his colleagues have shown that these currents are mainly confined in a relatively narrow ($\sim$90 km) layer of the upper ionosphere of Venus. These currents are closed in the solar wind downstream from the bow shock, in a transition layer. The direction of these electric currents depends on the direction of the interplanetary magnetic field (IMF) component perpendicular to the Sun-Venus line. According to the Pioneer Venus Orbiter data, the dynamic pressure of the solar wind is usually balanced by the magnetic field pressure in the magnetic barrier which is also equal to the kinetic pressure of the ionospheric plasma at the ionopause of Venus.

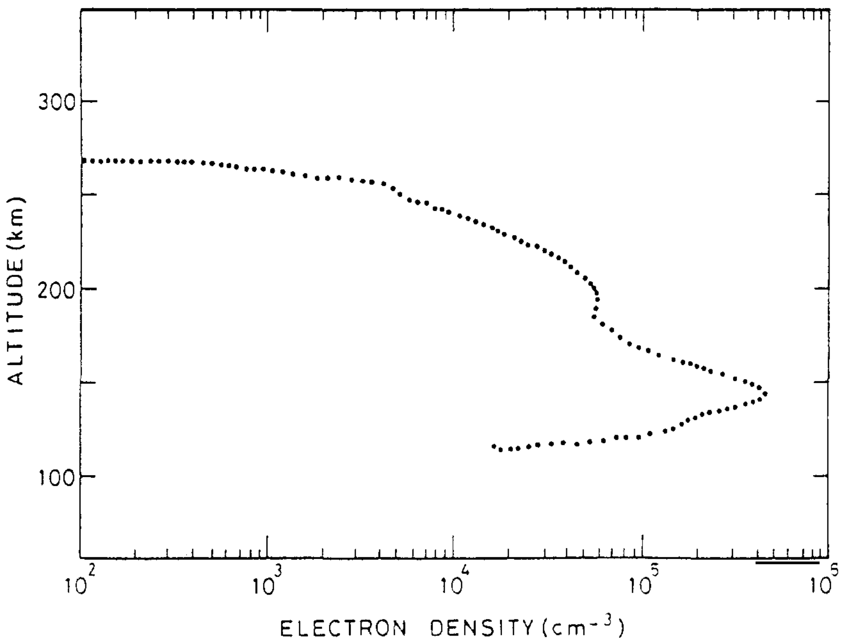

Fig.12.2. Height distribution of the electron density n_e in the day-side ionosphere of Venus, from Venera-10 radio occultation observations. The sharp upper boundary of the ionosphere, the steep decrease of n_e with height, i.e. the ionopause, is also observed by Mariner-5 and -10 and Pioneer Venus Orbiter.

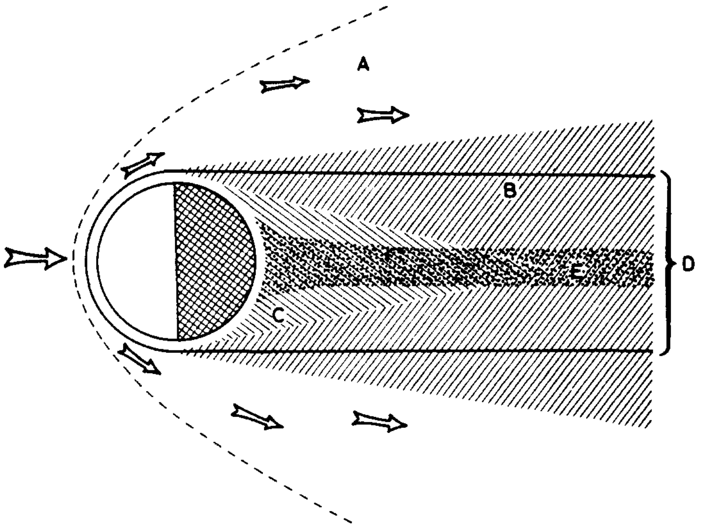

Fig.12.3. Schematic diagram of the bow-shock and the magnetosphere of Venus from the data of Venera-9 and -10. The arrows show the direction of the solar wind plasma stream. Region A is the transition region downstream from the bow-shock; region B is the boundary layer. Region C is the corpuscular umbra; the solid line shows the boundary of the magnetosphere (region D). Region E is the plasma sheet inside which the neutral layer is located that separates oppositely directed field lines.

Magnetic and plasma measurements onboard Venera-9 and -10 revealed that Venus has an extended plasma-magnetic tail similar to the magnetotail of the Earth. This magnetotail is shown in Fig.12.3; it has a diameter which is slightly larger than the diameter of the planet itself. The magnetotail of Venus is composed of two bunches of oppositely directed magnetic field lines; the orientation of the layer separating these bunches depends on the IMF direction. Immediately behind the nightside ionosphere there is a cone-shaped region C of corpuscular shadow where the ion fluxes are essentially weaker than in the transition layer downstream from the shock. The apex of this cone is at about five Venus radii. Electron fluxes with energies ranging from ten to a few hundred eV are recorded inside the corpuscular shadow of Venus. These fluxes are variable in time and form the main contribution of the fluxes observed in the nightside ionosphere of Venus.

A general view of Venus' magnetosphere and the shock wave ahead of it is shown in Fig.12.4. A rapid increase in the magnetic field intensity as well as a decrease in the plasma fluxes are observed at the separation between the transition layer and the magnetospheric boundary layer of Venus in a rather similar way as for the Earth's magnetosphere. Figure 12.4 also shows a simplified current system which can produce a magnetic field distribution similar to that measured on the dayside and nightside of the planet Venus.

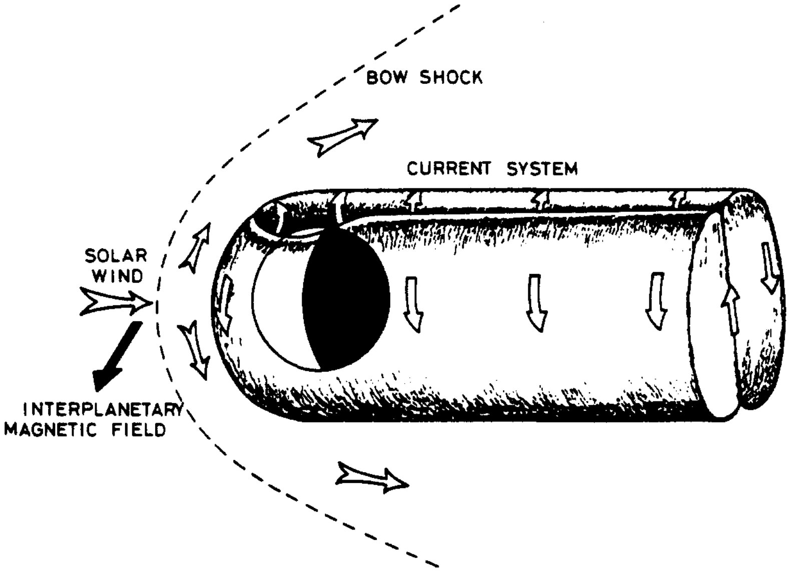

Fig.12.4. A possible simplified current system that forms "the magnetic barrier" ahead of Venus and the magnetic tail behind it. The orientation of the θ current structure in the magnetospheric tail changes with the changing orientation of the interplanetary magnetic field component perpendicular to the Sun–Venus line.

12.3.2. Magnetosphere of Mars

The existence of a bow shock in front of the planet Mars was first discovered by magnetic field measurements from Mariner-4 in 1954. Other information on the magnetosphere of Mars was obtained with Mars-2 and -3 in 1971 and 1972 and Mars-5 in 1974, which were equipped with magnetometers and instruments for plasma measurements. These three spacecraft did not approach the planet closer than 1100 km. Furthermore, the instruments for plasma and magnetic field measurements were not switched on each time that the satellites passed close to the planet; these instruments were operated intermittently, every 2 or 10 min in the case of Mars-2 and -3. This mode of operation limited the spatial and temporal resolution of the data. For these reasons quite a number of problems concerning the Martian magnetosphere remain unsolved.

Nevertheless, the magnetospheric boundary of Mars could be determined in the same way as for the other planets, including the Earth, from the increase in the magnetic field intensity, and from the decrease of plasma fluxes when the spacecraft penetrates from the transition layer (downstream from the bow shock) into the magnetosphere itself. From all crossings of the magnetosphere of Mars, it can be concluded that its shape very much resembles that of the Earth's magnetosphere. From the altitudinal distribution of the electron density, it can be concluded that the ionopause is usually absent in the dayside ionosphere of Mars (see Fig.12.5, compare with Fig.12.2). This suggests that the solar wind interaction with Mars differs from that with Venus; indeed the Martian ionosphere is shielded from the solar wind by the intrinsic magnetic field of Mars. The presence of such a magnetic field is confirmed by the fact that the diameter of the Martian magnetotail is 3.2 $\underline{R}_M$, larger than the planetary optical shadow of 2 $\underline{R}_M$. By contrast, the magnetotail of Venus has a diameter of 2.2 $\underline{R}_V$.

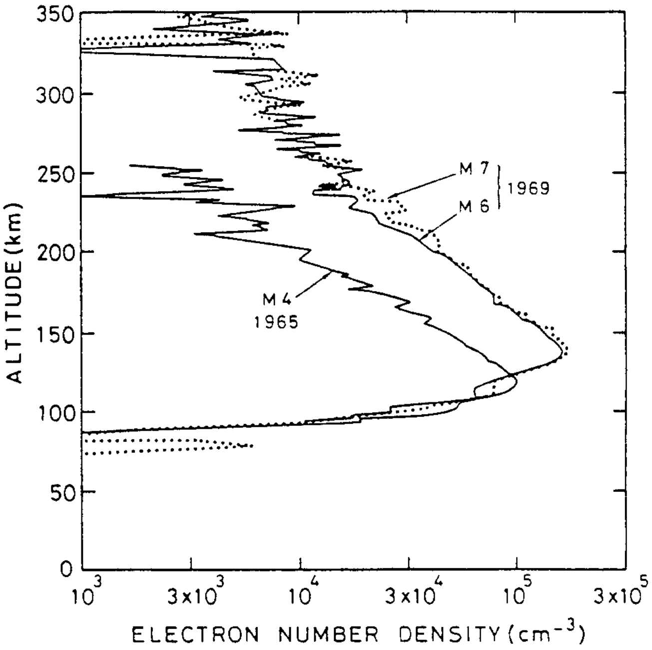

Fig.12.5. Vertical distribution of electron density in the dayside ionosphere of Mars from the radio occultation data obtained by Mariner-4, -6 and -7. No dayside ionopause was observed.

The mean position of the Mars magnetotail boundary was determined from the data of Mars-5 which crossed the magnetotail several times. However, no satellite has yet penetrated into the optical shadow of the planet; therefore, data on the internal structure of the Martian magnetosphere are still missing. However, upper limits to the magnetic moment of Mars can be estimated to be 2×10^{22} G cm^3. From the approximate shape of the Martian magnetosphere it can be deduced that the planet has a dipole magnetic field, the inclination of which to the Martian equator probably exceeds 20°.

12.3.3. Conclusions

Evidence for the presence of magnetic fields near a planet is not proof of the existence of an intrinsic planetary magnetic field. Indeed, in the case of Venus, a magnetosphere-like structure is formed with a magnetotail as a consequence of currents flowing in the ionosphere around the planet. Many more details of the interaction between the ionosphere of Venus and the solar wind will be obtained from Pioneer Venus Orbiter observations. The degree of ionization of the ions trapped in the Venusian atmosphere is not known; measurements which can determine the energy and also the mass of the ions, i.e. an ion energy-mass spectrometer, are required.

Several processes occurring in the Martian magnetosphere are not understood. An ion energy-mass spectrometer on a spacecraft passing through the Martian magnetotail would give new information on the interaction between the solar wind and Mars. The precise determination of the magnetic moment of Mars requires a low altitude satellite orbiting around Mars equipped with a sensitive magnetometer.