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COMPARATIVE MAGNETOSPHERES

The interaction between rotating planetary magnetic fields and the solar wind creates enormous flowing regions of plasma—Jupiter's dwarfs the Sun—whose behavior bears on a broad set of astrophysical problems.

A major discovery to emerge from the era of spacecraft investigations of the solar system is the high degree to which planetary magnetic fields organize ionized matter. The spectacular images of planetary surfaces, atmospheres, and satellites beamed to Earth by unmanned spacecraft have attracted much attention. However, the discovery of unexpected large-scale plasma formations within the magnetospheres of the planets is equally important because the behavior of these plasmas gives us insight into the way plasmas behave on cosmological scales.[1]

Radio waves emitted by planetary plasmas bear on a broad set of astrophysical problems and therefore occupy a central place in solar-system plasma physics. By mapping the plasma populations around Earth and other planets and by determining the physical mechanisms that operate in these plasmas, space-plasma physicists and astronomers are developing models with which to interpret electromagnetic emissions received from distant stars and galaxies. Many nonemitting wave and particle interactions play a crucial role in generating the observed astronomical emissions. This has made it essential to examine the plasma processes in situ with spacecraft. Much of the information presented here comes from such spacecraft measurements.

In this article, we describe very generally the salient features of planetary magnetospheres in the solar system. We address both the similarities in their plasma organization and the profound differences that exist among them. Earth's magnetosphere, shown schematically in Fig. 1, gives us a framework for discussing other planetary magnetospheres. While in some respects this magnetosphere is unique, it is also the cosmic plasma environment studied most thoroughly.[2,3,4] Hence, after a brief discussion of planetary magnetospheres in general, we will look in some detail at Earth's magnetosphere. Then we will turn to the other planets, comparing their magnetospheres with each other and with that of Earth.

GENERAL FEATURES

Ionized matter on planetary scales throughout the solar system is efficiently organized by the intrinsic magnetic fields or ionized atmospheres of planets and satellites. The resulting magnetospheres are, in essence, "cells"[1] of plasma that are semi-isolated and considerably different from neighboring plasma regimes. Planetary magnetospheres share many general features, including convective and corotational plasma flows, plasma tori of various origins, the production of plasma waves and radio emissions at most frequencies, and, most importantly, the ability to accelerate ions and electrons from thermal energies to tens and hundreds of megavolts. Many basic plasma processes and instabilities, such as the reconnection of magnetic field lines, wave-particle interactions, electrostatic double layers, and the Kelvin-Helmholtz instability, occur in planetary magnetospheres. A distinguishing feature is whether the magnetosphere is driven primarily by the solar wind or by planetary rotation.

The fundamental concept of a magnetosphere also applies to many phenomena observable in the galaxy and the universe. Figure 2 summarizes the relative sizes and configurations of various magnetospheres that exist in the universe. We know that ionized matter is organized on scales ranging from 10^3 kilometers, corresponding to a small planet such as Mercury, to 10^{18} kilometers, corresponding to a large radio galaxy such as New Galactic Catalog 1265. It is intriguing that the sizes of the magnetospheres of Earth and of pulsars are similar, although the energies involved are vastly different.

Planetary and stellar magnetic fields organize ionized matter in stellar and galactic systems. This organization has obvious implications for astrophysics, since the plasma processes involved often produce radio waves, X rays, and gamma rays, which propagate large distances and can be detected at Earth. The detection of such emissions confirms the existence, and sometimes the structure, of the magnetospheres that pervade our galaxy and the universe.

Planetary magnetospheres are formed by the interaction of the solar wind, which is the outward expansion of the solar corona, and the intrinsic magnetic fields and plasmas of the individual planets.[5] (The problem of

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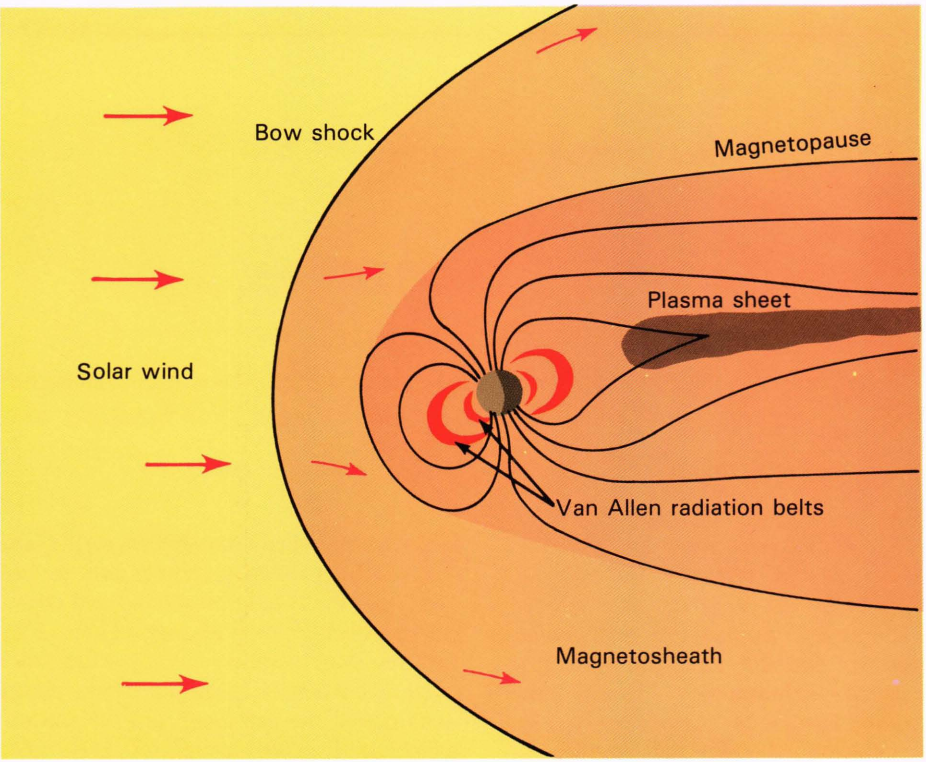

Figure 1—Earth's magnetosphere. The sketch shows important features of the plasmas and waves in the magnetic fields that surround Earth.

how planetary magnetic fields are generated is beyond the scope of this article.) The dynamic pressure of the solar wind plasma, with its embedded solar magnetic field, and the strength of the planetary magnetic field determine the overall size of an individual magnetosphere. However, as we will see for Jupiter, plasmas within the magnetosphere can also play a significant role.

At Earth's orbit, the solar wind has an ion density of about 10 per cubic centimeter, the energy density is a few times 10^{-8} dynes per square centimeter, and the magnetic field intensity is about 5 nanoteslas. These quantities decrease approximately as the inverse square of the distance from the Sun. There are large variations around nominal values such as these, changing the configurations of the planetary magnetospheres. The solar wind "blows" with a velocity V that is normally about 400 kilometers per second. This velocity is "super-Alfvénic," that is, it substantially exceeds the Alfvén velocity, which is the characteristic signal velocity in a completely ionized gas. The Alfvén velocity is given by $B/(4\pi\rho)^{1/2}$, where B is the strength of the planetary magnetic field and ρ is the ion density in the solar wind. Imposing an object such as a planet, comet, or asteroid into the flow produces a collisionless shock wave in the solar wind upstream. This phenomenon is analogous to the generation of a shock wave in front of an airplane traveling at a velocity higher than the local atmospheric speed of sound.

One can make a rough estimate of the location of a planet's magnetopause stagnation point—the boundary of its magnetosphere in the direction of the Sun—by equating the dynamic pressure $C\rho V^2$ of the solar wind and the sum of the magnetic field and plasma pressures:

$$C\rho V^2 = B^2/8\pi + P .$$

Here C is a constant, $B^2/8\pi$ is the pressure due to the magnetic field of the magnetosphere at the boundary, and P, which is often negligible, is the gas pressure inside the magnetosphere. This good first approximation ignores the physical processes that may operate at a magnetosphere boundary, such as electric currents resulting from interconnecting interplanetary and planetary magnetic fields. In a dipole field geometry, a planet's external magnetic field B decreases as the inverse cube of the distance from the center of the planet, so knowledge of the planet's surface magnetic field allows one to calculate the location of the magnetopause.

EARTH

Earth's subsolar magnetopause is normally located about 10 Earth radii from the center of Earth. However, disturbances in the velocity or ion density of the solar wind—V or ρ in the above equation—can cause considerable changes in the size of Earth's magnetosphere. At

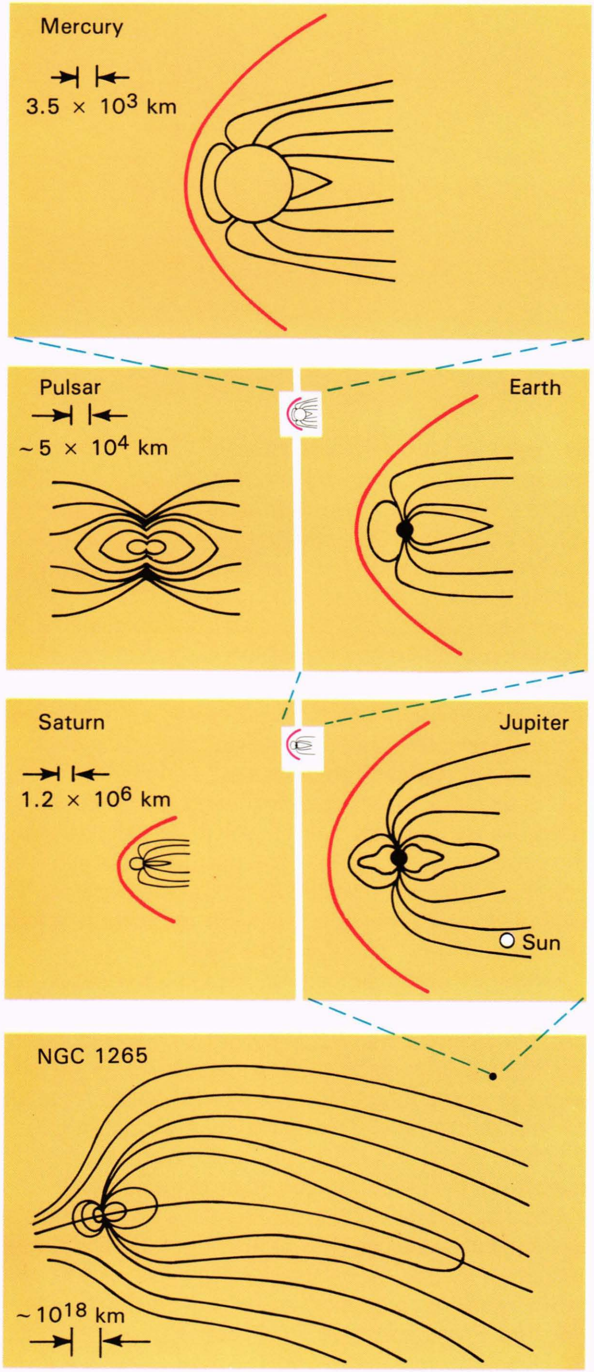

Figure 2—Sizes of magnetospheres in the universe. While the sizes of the magnetospheres of Earth and pulsars are similar, the energies involved are vastly different.

times, the magnetopause is at a geocentric distance as small as four to five Earth radii, inside the orbit of synchronous communication satellites, as Table 1 indicates. While the most recognized features of Earth's magnetosphere are the Van Allen radiation belts, these belts are actually only the high-energy "tails" of the plasma distributions that control the dynamics of the environment.

In general, the regions of the magnetosphere (Fig. 1) are delineated by the density, temperature, and composition of the resident plasma population. The solar wind, consisting primarily of H^+ and He^{++} ions, is thought to be the dominant source of plasma in the outer magnetosphere, while Earth's ionosphere supplies H^+, He^+, and O^+ ions to the ring-current region and often to the nighttime plasma sheet. We do not yet know the details of how solar wind plasma enters the magnetosphere; the fraction entering is in the range of about 10^{-2} to 10^{-4} of the solar wind number density.

As Fig. 1 shows, the inner Van Allen radiation belt, consisting primarily of high-energy protons with energies greater than 20 megavolts, is contained within the plasmasphere, a region of cold electrons and protons of ionospheric origin, electronvolt energies, and a density greater than 1000 per cubic centimeter. This plasma is in approximate equilibrium with the ionosphere. Inside the plasmasphere, an electric field is produced by the lines of magnetic force, which corotate with Earth because they are anchored in the conducting plasma of the ionosphere. The ionosphere itself is coupled, via collisions, to the atmosphere and therefore to Earth's surface.

Outside the plasmasphere, there is cold plasma with a density of the order of 1 per cubic centimeter that is often augmented by a hotter plasma, of energy on the order of 10 kilovolts, extending outward from the plasmasphere boundary for one to two Earth radii. This hot plasma "ring" can store a significant amount of energy—on the order of 10^{21} ergs—and it grows or decays in intensity depending on geomagnetic activity. Indeed, under some conditions the ratio of particle pressure to magnetic field pressure in the plasma ring—its "beta"—can approach 1, producing various types of plasma instabilities. The outer Van Allen radiation belt contains electrons with energies of 1 megaelectronvolt or more; it typically extends from the plasmasphere boundary to somewhat beyond the synchronous altitude, but it is highly time dependent, varying with geomagnetic activity.

Through viscous interaction (not incorporated in gas-dynamic analogues), the solar wind flowing past the magnetosphere produces a long comet-like plasma tail, whose anti-Sunward extent is unclear but certainly is greater than 1000 Earth radii. In the center of this magnetotail is embedded a plasma sheet of ions and electrons with typical temperatures of 5 to 10 kiloelectronvolts and densities of a few particles per cubic centimeter. As Fig. 1 indicates, the plasma sheet extends Earthward into the nightside auroral zones along magnetic field lines in both hemispheres. The "polar cusps" indicated in the figure are regions in the northern and southern hemispheres between the magnetic lines that close on the Sunward side of Earth and those swept into the magnetotail. Solar wind plasma can directly enter the cusp regions, which extend down to the ionosphere, to produce the dayside portions of the auroral zones.

The flow of the solar wind past the magnetopause produces a large-scale electric field directed across the magnetosphere—perpendicular to, and directed out of,

Table 1—Planetary properties.

	Solar Distance (AU)	*Radius* $(10^3 km)$	*Spin Period (days)*	*Synchronous Orbital Radius (planetary radii)*	*Average Density* (g/cm^3)	*Surface Gravity (N/kg)*	*Escape Velocity (km/sec)*
Mercury	0.4	2.42	58.6	100	5.4	3.6	4.2
Venus	0.7	6.10	243	254	5.1	8.7	10.3
Earth	1.0	6.37	1	6.6	5.5	9.8	11.2
Mars	1.5	3.38	1.02	6.0	4.0	3.7	5
Jupiter	5.2	71.4	0.41	2.3	1.3	26.0	61
Saturn	9.5	60.4	0.44	1.9	0.7	11.2	37
Uranus	19.2	25.6	0.72	4.5	1.18	9.4	22
Neptune	30.0	25.3	0.74	4.5	1.56	15.0	25

the plane of Fig. 1. This electric field, whose magnitude is typically of the order of 50 kilovolts over 20 to 30 Earth radii, is produced largely by the process in which the magnetic field lines of the interplanetary medium connect with those of the magnetosphere at the magnetopause. This "reconnection" process varies with time, depending importantly on the relative orientations of the geomagnetic field and the interplanetary magnetic field, which is highly time dependent owing to solar activity. Under some interplanetary field conditions, the electric field probably results from the viscous interaction, not reconnection.

The large-scale electric field, together with the ambient magnetic field, gives rise to $\mathbf{E} \times \mathbf{B}$ forces that move plasma from the geomagnetic tail into the near magnetosphere. The plasma is convected around the plasmasphere and tends to flow back tailward along the inner edges of the magnetopause. Thus the plasmapause (the boundary of the plasmasphere) is the position at which the large-scale electric field dominates the corotating electric field (Earth's rotating magnetic field viewed in a stationary reference frame). The flux tubes inside the plasmapause never open as they rotate with Earth.

Space scientists have done important research on the mechanisms by which energy is stored in, and sporadically released from, the geomagnetic tail. The solar wind puts energy into the geomagnetic tail at a rate of about 10^{19} ergs per second, which is about 1 to 10 percent of the solar wind energy that flows past the magnetosphere. During large magnetic disturbances, the average energy-dissipation rate is also on the order of 10^{19} ergs per second during an interval of 10^3 to 10^4 seconds. These episodic occurrences, called magnetic substorms, manifest themselves by large fluctuations in the magnitude and direction of the geomagnetic field measured at high-latitude observatories. If a magnetic disturbance is intense, the hot plasma "ring current" will depress the geomagnetic field intensity in the equatorial and mid-latitude regions for one to several days. The aurorae, which have been known since antiquity and have been written about at least since Aristotle, are visual evidence of these phenomena.

The process by which particles are accelerated during magnetic storms is not well known, but the conversion of the plasma's magnetic energy to mechanical energy is thought to involve the reconnection of magnetotail field lines or inductive acceleration. Energy conversion remains a major unsolved problem in magnetospheric physics. Theoretical work on the underlying physics of reconnection processes in laboratory and magnetospheric plasmas has proceeded in parallel, enabling research in one field to profit from that in the other.

A remarkable and well-known characteristic of the magnetospheric system is that its plasmas are energized to a distribution that extends from a few kiloelectronvolts to several tens of megaelectronvolts. There appear to be several energizing mechanisms, including betatron acceleration, resonant phenomena, and magnetic pumping.[6] The latter mechanism is thought to be largely responsible for the Van Allen belts. It operates through the conservation of a solar wind particle's magnetic moment as it diffuses into the inner magnetosphere. The mechanism is also thought to operate in other astrophysical environments, including the Sun.[7]

Magnetic pumping cannot explain completely the higher energy component of the inner Van Allen radiation belt, which contains protons with energies as high as 600 megaelectronvolts. The higher energy particles originate in the interaction of galactic cosmic rays and Earth's atmosphere. The neutrons produced in this interaction decay into protons and electrons that are trapped in orbits in the geomagnetic field.

The magnetosphere not only contains low-energy plasmas and energetic particles, it also supports a variety of plasma waves that have various energy sources and cover a wide range of frequencies. The flow of the solar wind past the magnetosphere produces, through the Kelvin-Helmholtz instability, hydromagnetic waves with frequencies ranging from 10^{-3} hertz (Alfvén waves) to 0.1 hertz. Plasma instabilities associated with magnetic storms and the high-beta ring current are also sources of such waves. Lightning discharges in the atmosphere stimulate the motion of electrons around magnetic field lines—electron gyro motion—producing whistler waves in the kilohertz range; these waves propagate along the field lines. Electromagnetic emissions and electrostatic oscillations in this frequency range are also produced by anisotropic particle populations that are trapped in the geomagnetic dipole field.

From the standpoint of remote sensing of astrophysical objects, the 10^9 watts of power emitted in the auroral radiation is of great interest. At the times of auroral displays, this radiation, centered around 200 kilohertz (wavelengths on the order of kilometers), is apparently produced above the ionosphere, possibly at altitudes up to an Earth radius. The question of the mechanism that produces it has yet to be settled. One interpretation sees its origin as the result of plasma double layers, or separations of charge, in the currents that go from the magnetosphere to the ionosphere along field lines. The plasma instabilities in the system are believed to generate the radio waves.

MERCURY, VENUS, AND MARS

A striking development in planetary magnetism was the discovery by the Mariner Venus-Mercury spacecraft that Mercury, a slow rotator (Table 1) scarcely larger than Earth's moon, has an intrinsic magnetic field that is the basis for a magnetosphere at the planet.[8] Mercury's low planetary magnetic moment (Table 2) and the higher solar wind density at the planet mean that its magnetopause is less than a planetary radius above its surface (Fig. 3a). Mercury has no appreciable atmosphere, so that particles confined by the magnetic field can hit the planet's surface directly. The apparent absence of an atmosphere also means the absence of an ionosphere, which, for Earth, provides the interface between the totally ionized magnetosphere and the less conductive atmosphere and planetary surface. These differences, together with Mercury's small magnetosphere, suggest that plasma processes in its magnetosphere differ from those around Earth. Mariner passed through the planet's magnetotail and detected bursts of cold and hot electrons, as well as more energetic electrons, in the 70 to 300 kiloelectronvolt range. It is likely that the time scale for magnetosphere dynamics is short, with the Mercury equivalent of magnetic substorms occurring on the scale of minutes rather than hours as at Earth. A strong solar wind could push Mercury's magnetopause down almost to the planet's surface, whereby the solar wind would strike the surface directly.

Venus, now studied for two decades by American and Soviet spacecraft, has no detectable intrinsic magnetic field (Table 2). The solar wind interacts directly with the top of the planet's ionosphere, forming a kind of planetary magnetosphere.[9] The boundary between the solar wind and the ionosphere is termed the ionopause, whose height can be roughly calculated from gas dynamics. The interaction is actually much more complicated than such calculations indicate and probably involves systems of induced currents and the interconnection of solar wind and induced magnetic fields. There is a bow shock upstream of the Venus ionopause, as Fig. 3b indicates, and a filamentary magnetotail on the planet's nightside to distances of at least 10 Venus radii. Insight gained in the study of the interaction between the solar wind and Venus applies to solar wind interactions with comets, particularly during their perihelion passages, and with Saturn's satellite Titan, which has an atmosphere but no detectable magnetic field.

The Martian magnetosphere is not understood, even though numerous spacecraft have been to the planet.[8] There is evidence of a bow shock, as sketched in Fig. 3c, but there is no agreement on the magnitude of any internal magnetic field. Some evidence suggests that the solar wind interacts with the ionosphere at the top of the tenuous Martian atmosphere, whose pressure at the surface is only 5 millibars. There is no information as to whether this interaction is normal or whether there might be a magnetopause under some solar wind conditions. The nature of the interaction between the solar wind and the ionosphere is basic to understanding the evolution of the Martian atmosphere. If Mars has no significant planetary magnetic field, it is possible that

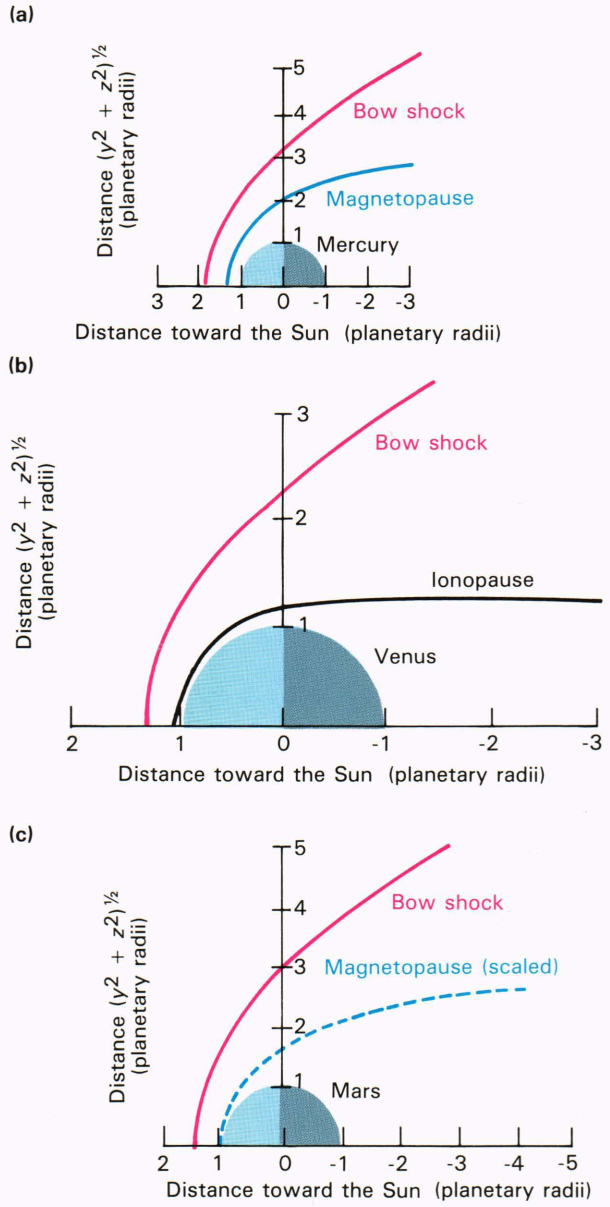

Figure 3—Bow shock and magnetopause profiles. The curves represent the average bow shock and magnetopause positions and shapes for (a) Mercury, (b) Venus, and (c) Mars. All three planets are drawn to the same distance scale for comparison. Table 1 gives values for the planetary radii. (Adapted from Ref. 35).

Table 2—Planetary magnetic parameters.

	Dipole Moment (gauss cm^3)	*Equatorial Surface Field (gauss)*	*Polarity (with respect to Earth)*	*Angle of Magnetic Axis (degrees to rotation axis)*	*Plasma Sources**	*Typical Magnetopause Position (planetary radii)*
Mercury	$\sim 3\times 10^{22}$	0.0035	Same	~ 10	W	1.1
Venus	$< 10^{21}$	< 0.0003	—	—	A	1.1
Earth	8×10^{25}	0.31	Same	11.5	W,A	10
Mars	2.5×10^{22}(?)	0.00065(?)	Opposite	—	?	?
Jupiter	1.5×10^{30}	4.1	Opposite	~ 10	W,A,S	60-100
Saturn	1.5×10^{29}	0.4	Opposite	< 1	W,A,S	20-25
Uranus	3.9×10^{27}	0.23**	Opposite	60	A,S(?)	18-25
Neptune	?	?	–	–	?	?

*W = solar wind; A = atmosphere; S = satellites

**Because of the offset dipole, the surface field ranges from 0.1 to ~ 1.1 gauss.

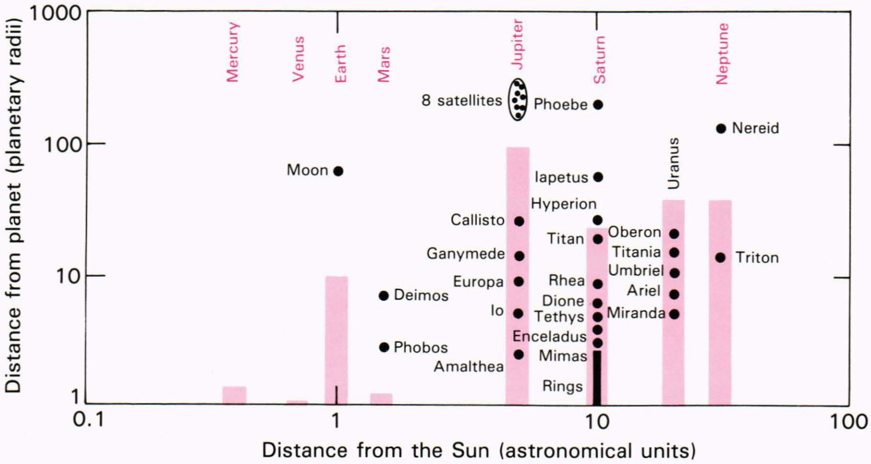

Figure 4—Magnetosphere sizes, satellite locations, and planetary orbital radii. Each vertical bar represents the distance from the center of a planet to the Sunward boundary of its magnetosphere, in units of the planet's radius. The magnetosphere size for Neptune is an estimate. (Adapted from Ref. 5.)

the solar wind has "scavenged" atmospheric constituents, leading to today's tenuous atmosphere.

THE OUTER PLANETS

As Fig. 4 indicates, solid material in the form of rings and moons is embedded deep inside the magnetospheres of Jupiter and Saturn, and most likely inside the magnetospheres of Uranus and Neptune. Of course, Earth's moon is found inside the magnetotail for a few days every 28 days. However, we have never discerned a significant lunar influence on geomagnetic activity (or the converse). If Mars has a small magnetosphere, its two moons, Phobos and Deimos, would also occasionally be in its magnetotail, but these small rocky bodies would not have a significant influence on the plasma dynamics.

By contrast, the Galilean satellites play an essential role in locally modifying the particle fluxes around Jupiter and contribute to the ion population in that planet's magnetosphere. The moons and rings of Saturn help deplete the energetic particle populations in its magnetosphere and may be sources for low-energy ions such as oxygen. Titan may be an important source of plasma for the outer Saturnian magnetosphere.

JUPITER

Jupiter is the largest planet in the solar system and has, as well, the largest magnetosphere discovered to date.[10-13] It extends some 50 to 100 Jovian radii in the Sunward direction, as Fig. 5 indicates, and at least 6 astronomical units in the anti-Sunward, or magnetotail, direction.[14] If the Jovian magnetosphere were visible from Earth, it would make a larger image in the sky than the Sun, even though it is four times farther from Earth. Note from Fig. 5 that it took the Voyager 2 spacecraft, traveling at about 35,000 kilometers per hour on the average, about 32 days to cross a portion of the magnetosphere. Figure 5 also shows other unusual features of Jupiter's magnetospheric plasma:

1. There is a periodicity in the plasma density related to the spin of the planet; this showed up most clearly during Voyager's outbound trajectory.
2. The spacecraft encountered the planetary bow shock and magnetopause several times, both inbound and outbound, suggesting great variability in the pressure balance between the solar wind and the planetary magnetic field.

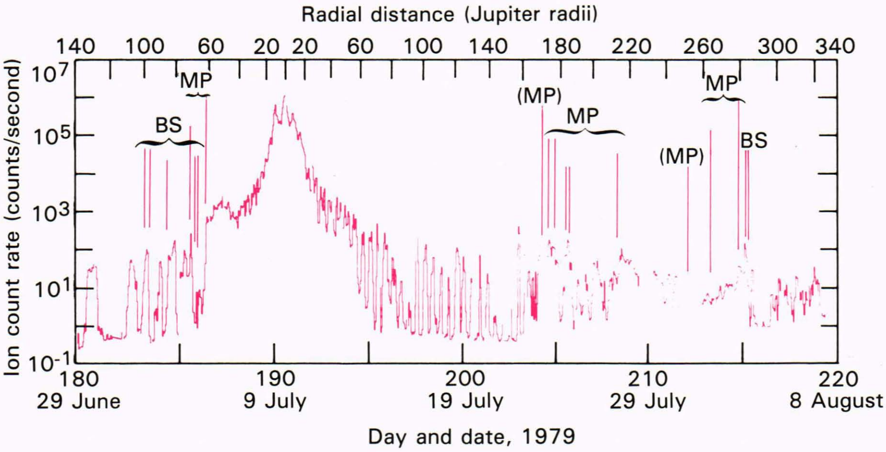

Figure 5—The ion counting rate profile measured during the Voyager 2 encounter with Jupiter. The notations BS and MP indicate the spacecraft's encounter with the planet's bow shock and magnetopause, respectively. Voyager 2 spent nearly 20 days inside Jupiter's magnetosphere. (From Ref. 14.)

3. The ion intensity increased rapidly inside about 30 planetary radii as the spacecraft approached the orbits of the Galilean satellites.

Why the observed spin-related periodicity? The magnetic fields of rotating celestial bodies impart angular velocity to local plasma, causing a centrifugal force that stresses the field. By this mechanism a large-radius ring of current, called a magnetodisk, forms around the planet or, equivalently, the planet's magnetic field lines stretch out so that the Lorentz force $\mathbf{J} \times \mathbf{B}$ in the magnetospheric plasma balances the centrifugal force of the rotating plasma. The 9.6 degree tilt of the Jovian dipole with respect to the rotation axis (Table 2), together with the planetary rotation, causes the periodicity. Periodicity can also arise from a longitudinal asymmetry in a planetary system. Reference 15 contains a discussion of various theoretical proposals to account for periodicities.

Data from the Voyager spacecraft indicate that the centrifugal force balances about 25 percent of the inward Lorentz force,[16] while pressure gradients in the high-beta, 30-kiloelectronvolt hot plasma of the Jovian magnetodisk balance the remaining 75[14] percent. Thus, the high-beta plasma and the centrifugal force inflate the magnetosphere, pushing its dayside boundary to distances of 60 to 100 Jupiter radii, which is much farther than the distance the intrinsic planetary magnetic field can support alone, approximately 45 radii, when the plasma pressure P is very small.

The Voyager spacecraft also discovered that the plasma populating the Jovian magnetosphere originates within the magnetosphere. Atoms and molecules can sputter from the surfaces of the Galilean satellites and emanate from the volcanoes of Io. Electron impact, charge exchange, or solar photons can ionize these particles, which can then immediately participate in or alter the many plasma processes occurring within the magnetosphere. Changes in the internal sources or in the solar wind explain the large excursions of the magnetosphere near the dayside boundary observed by the Voyager (Fig. 5) and Pioneer spacecraft. Because of the important role of plasma pressure, the Jovian magnetosphere differs radically from that of Earth, where the pressure $B^2/8\pi$ from the vacuum magnetic field stands off the pressure of the solar wind.

Through its incessant volcanism, Io supplies gases at a rate of about one ton per second. These gases – predominantly sulfur dioxide – can enter the magnetosphere directly or, as is most likely, are frozen out on the surface and then sublimate or sputter away. After ionization by photons or magnetospheric particles, these new heavy ions, primarily sulfur and oxygen, are magnetically trapped by the corotating planetary magnetic fields. At the orbit of Io, a cold plasma torus, consisting primarily of sulfur and oxygen, circles Jupiter. The Voyager spacecraft measured these ions, as shown in the data in Fig. 6.[17-20] Ion densities in the torus reach about 2000 per cubic centimeter, high enough to affect the propagation of radio and plasma waves originating inside Io's orbit. In addition, there appears to be a closed conducting circuit between Jupiter's ionosphere and Io containing current flowing along Jovian field lines. Such a circuit would be completed by the ionospheres of Jupiter and Io. The relative motion between Io and the rest of the circuit induces a large net electromagnetic force of about 600 kilovolts, with a 2- to 3-megampere current flow measured by Voyager 1.[20]

The plasma in the torus at Io's orbit diffuses outward because of the centrifugal force due to the rotation of Jupiter, which produces a multispecies plasma sheet, or magnetodisk, extending from Io to the magnetosphere boundary. This cold plasma of energy about 10 electronvolts loads up Jupiter's magnetic field lines beyond Io so that the conductivity of the Jovian ionosphere cannot force this part of the magnetosphere into rigid corotation. At larger radial distances, beyond about 30 planetary radii, the plasma is dilute and much hotter – about 30 kiloelectronvolts – so that again one observes near-rigid corotation out to the magnetopause on the dayside and to about 80 planetary radii on the early morning side. Thus the Jovian plasmasphere can be thought of as occupying the entire volume of the magnetosphere, in contrast to the situation at Earth depicted in Fig. 1.

A remarkable characteristic of Jupiter's environment is the large number of energetic ions and electrons populating and escaping from the magnetosphere. Ion ener-

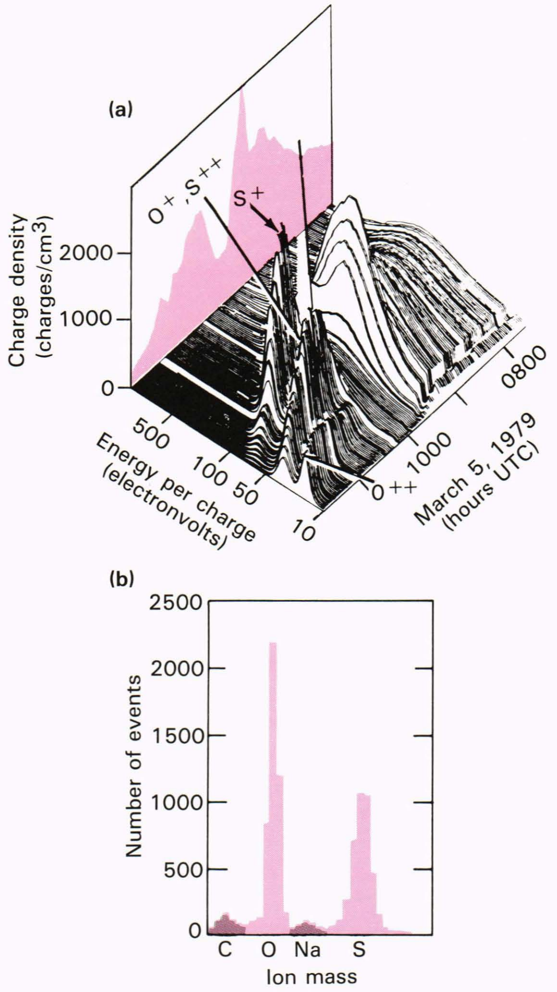

Figure 6—The energy spectra and composition of ions in Jupiter's magnetosphere. (a) The ion distribution as a function of energy per charge and time as measured in the inner Jovian magnetosphere near the orbit of Io by the plasma instrument on Voyager 1. (From Ref. 15.) (b) The elemental composition of the Jovian magnetosphere determined by the low-energy charged particle instrument on Voyager 2. A large abundance of oxygen and sulfur compared to carbon is evident in the data, which Voyager collected about 12 Jovian radii from the planet. (From Ref. 23.)

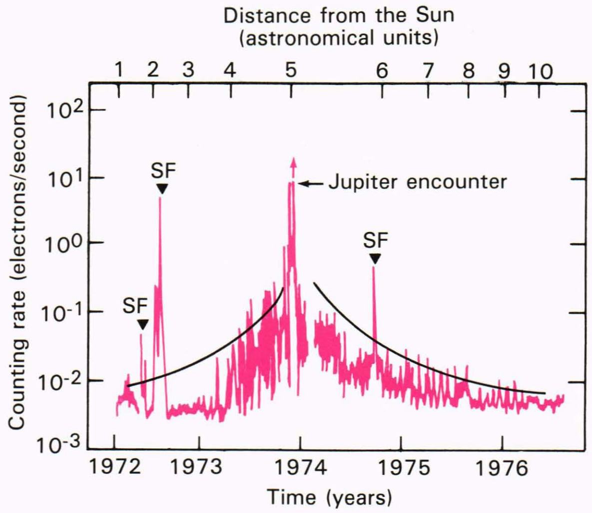

Figure 7—Interplanetary electrons measured by Pioneer 10 as it encountered and passed Jupiter. The peaks labeled SF are due to electrons produced by solar flares. The detector counted electrons with energies of 3 to 6 megaelectronvolts. (From Ref. 21.)

gies range from 30 kilovolts to over 100 megavolts, while electron energies range from a few kiloelectronvolts to over 40 megaelectronvolts. What had been thought, prior to 1974, to be "cosmic ray" electrons are simply electrons escaping Jupiter's magnetosphere and filling the entire solar system, as shown by the Pioneer data in Fig. 7.[21] The energy spectrum of these electrons extends to over 40 megaelectronvolts, and the shape of the spectrum exhibits a clock-like periodicity of about 10 hours, which is approximately Jupiter's period of rotation. Energetic ions, that is, those with energies above about 30 kiloelectronvolts, also escape the magnetosphere and have been observed as discrete increases in intensity as far as 0.7 astronomical unit from the planet.[22] Measurements of the ion composition in the 1-megaelectron-volt-per-nucleon range (Fig. 6b) show oxygen and sulfur in much greater abundances than in the solar system as a whole.[23]

Very intense fluxes of electrons with energies of over 10 megaelectronvolts and ions with energies over 100 megaelectronvolts occur deep in the Jovian magnetosphere. These fluxes produce some of the intense radio emissions from the planet measured at Earth. Maps of the emissions made by the Very Large Array radio telescope in New Mexico allow us to observe the structural and temporal changes in the inner Jovian magnetosphere to distances of about three Jupiter radii from the center of the planet.

The radio spectra in Fig. 8 include Jupiter's emissions. The emissions due to Io are probably the result of the intense electromagnetic coupling between that satellite, the plasma torus, and the upper ionosphere or atmosphere of Jupiter. As we noted earlier, Alfvén waves are generated by the movement of Io, which is possibly a conducting body, through the Jovian magnetospheric plasma, which is itself partially caused by Io's volcanism.

Scientists who study space plasmas have proposed several mechanisms to explain the accelerated electrons and ions in the Jovian magnetosphere. The mechanisms involve adiabatic or quasi-adiabatic processes and are based on the three invariants of particle motion in a dipole-like field. These processes alone cannot accelerate particles to the highest energies observed in the Jovian magnetosphere. However, a quasi-adiabatic process with repeated cycles of adiabatic inward transport of particles followed by nonadiabatic scattering can increase particle energies substantially.[24] This resembles the general Alfvén magnetic-pumping process, which we referred to earlier for Earth's magnetosphere.

Other acceleration mechanisms in the outer magnetosphere begin with the photoionization of neutrals escaping from Io's torus. The **V** × **B** electric field accelerates the newly formed ions to velocities up to 1000 kilometers

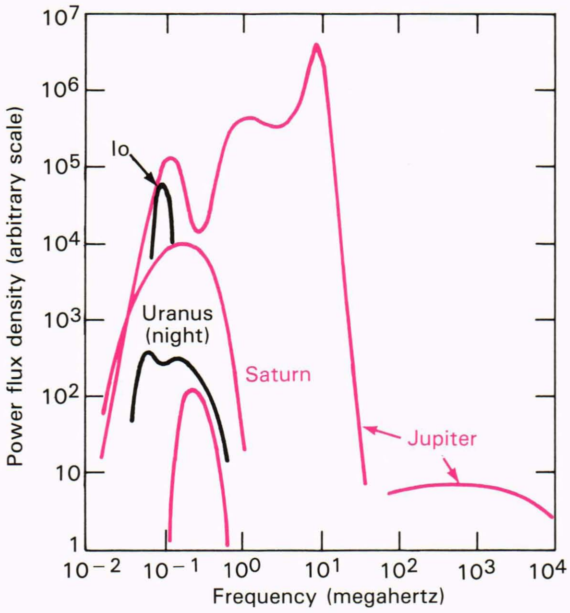

Figure 8—Radio power spectra. The curves represent the nonthermal emissions from the magnetospheres of Earth, Saturn, Jupiter, the moon Io (whose orbit is inside Jupiter's magnetosphere), and Uranus. The emissions data are normalized to show the intensities as they would be observed at the same distance from each planet. (Adapted from Ref. 36.)

per second at distances of 80 planetary radii; this means translational kinetic energies of about 83 kiloelectronvolts for oxygen and twice that for sulfur. The ions can then undergo inward transport and adiabatic compression[25] with subsequent energy increases by factors up to 10^3.

Recent research[14] has addressed the overall mass and energy balance in the Jovian magnetospheric system. Io produces an estimated 2×10^{28} ions per second, representing an energy input of 2×10^{19} ergs per second. The input from the neutral cloud in Io's orbit is roughly similar. Jupiter's upper atmosphere contributes an estimated 10^{28} hydrogen ions per second, with an energy of 3×10^{21} ergs per second derived from Jupiter's rotation. Finally, the solar wind contributes 10^{28} hydrogen ions per second and perhaps 3×10^{20} ergs per second. Observations of energetic particles suggest the loss of hot plasma through a nightside magnetospheric wind of 2×10^{27} ions per second and 2×10^{20} ergs per second. Ions precipitating to form Jupiter's aurorae deposit about 2×10^{21} ergs per second. The magnitudes of these numbers suggest that only Jupiter's rotation can drive this giant magnetosphere. Thus Jupiter's magnetosphere, which is driven from within by the central body's rotation and whose plasma comes from internal sources, is currently the best and only analogue to the physical processes that may operate in pulsars.

SATURN

Major surprises from the first spacecraft encounter with Saturn—the Pioneer 11—were the small magnitude of the planetary magnetic field and the nearly perfect alignment of the magnetic dipole axis with the rotation axis. After seeing the data from Jupiter, planetary scientists had fully expected that the surface magnetic intensity of Saturn would be similar to, but somewhat smaller than, that of the largest planet. That it was only a small fraction of Jupiter's surface intensity (see Table 2) emphasizes how much we must learn about planetary magnetism and magnetic dynamos. Indeed, the small size of the Saturnian dipole moment suggests that the planet has a small conducting core or a slow variation in its dynamo (although no clear evidence for such a change appeared in the several-year interval between the Pioneer and Voyager encounters with Jupiter).

Saturn's small magnetic moment limits the size of its magnetosphere under normal conditions of the solar wind.[26,27] As with the magnetopauses of other planets, enhanced solar wind pressure pushes the magnetopause of Saturn toward the planet. Indeed, the Voyager 2 spacecraft encountered the magnetopause at approximately 19.7 Saturnian radii, whereas Voyager 1 detected the same boundary at approximately 26, well beyond the orbit of the moon Titan.

The Pioneer spacecraft found evidence of a cold plasma, primarily oxygen, near Saturn's E-ring—a ring whose radius is 4 to 6 times that of the planet—and a more tenuous plasma farther out. The Voyager 1 plasma instrument found evidence for a cold plasma encompassing the orbit of Titan and extending to the magnetopause on the dayside. The low-energy charged-particle experiment on Voyagers 1 and 2 found evidence[28] for a hot plasma in the magnetosphere, with characteristic energies on the order of 20 to 55 kiloelectronvolts. This hot plasma region appears to be confined between the orbits of Tethys and Rhea and probably encircles the planet. There is also sufficient hot plasma in the outer magnetosphere, where the pressure ratio β is 0.5 to 1, to suggest that the interaction between the solar wind and Saturn is more like the interaction at Jupiter than at Earth, especially during the Voyager 2 encounter. However, the three rapid flybys of the planet have been insufficient to characterize the "normal" plasma conditions or dynamics in the magnetosphere.

The populations of energetic particles are depleted in the vicinity shared by the E-ring and the satellites Dione and Tethys. This may be due in part to particle absorption by the E-ring material and the moons embedded in the magnetosphere. If the particles of the E-ring absorb low-energy ions on impact, the ions will sputter material from the grains. Based on this process, one can estimate that if the E-ring is made up of 10-micron particles and the impacting ions are protons, it will survive at most 10^5 years. Surprisingly, there are sources of low-energy ions (probably O^+) and electrons interior to the orbit of Enceladus; the nature of the sources is not yet clear.

Galactic cosmic rays have easy access to Saturn's magnetosphere, moons, and rings because of the planet's small magnetic moment. Space scientists have devoted considerable effort to calculating the neutrons expected from cosmic-ray impacts on Saturn's innermost rings. The spectrum of high-energy protons in the 50 megaelectronvolt range in the planet's inner magnetosphere, as measured by Pioneer and Voyager, supports the idea that cosmic rays produce neutrons from ring materials. Such neutrons decay into protons and electrons, both of which are trapped by the planetary field.

URANUS

One of the more intriguing magnetospheres in the solar system is the one surrounding Uranus, which is unique among the planets in that its spin axis lies nearly in the plane of its orbit around the Sun, rather than perpendicular to it. It was thought prior to January 24, 1986, that the dipole axis of Uranus' magnetic field is likely to be approximately parallel to the spin axis, as is the case for the other planets. If this were so, the solar wind would be incident upon a dipole magnetic field oriented at 90 degrees to that of the other planetary magnetospheres. Further, at the time of the Voyager 2 encounter, the spin axis of the planet was pointing approximately at the Sun, so that the solar wind was incident on a "polar" region of the planet. These expectations, based on our knowledge of the magnetospheres of the other planets, turned out to be substantially in error.

The magnetic field of Uranus was shown by Voyager to be tilted at an angle of approximately 60 degrees to the rotation axis, the largest such inclination of any of the planets and similar to oblique rotators inferred from some astrophysical objects (see Table 2 and Ref. 29). The dipole moment is offset by about 0.3 Uranian radii along the axis of planetary rotation toward the planet's nightside. The strength of the equatorial field at approximately 0.23 gauss is similar to that of Saturn, and the standoff distance of the magnetopause in terms of planetary radii (Table 2) is also similar. Inside the magnetosphere are trapped large numbers of energetic electrons but a relatively lower number of energetic ions, when compared to Jupiter and Saturn. The low-density (approximately 1 per cubic centimeter) plasma consists principally of protons[30] with an extremely low ($\lesssim 10^{-4}$) helium-to-proton ratio at the higher ($E \gtrsim 0.5$ megaelectronvolt per nucleon) energies.[31] The radiation trapped within the Uranian magnetic field is significantly affected by absorption from the major Uranian satellites.

Planetary radio emissions extending from 30 to 800 kilohertz are found to be strongest on the nightside of the planet,[32] while plasma waves with frequencies as low as 10 hertz are found throughout the magnetosphere.[33] Uranus is unique among the planetary magnetospheres investigated so far in that the plasma β is less than approximately 0.1, i.e., as close to a "vacuum" magnetosphere as has ever been observed. The intensity of the radiation belts is such that bombardment by energetic protons on methane ice would turn it into a black residue with very little reflectivity within a few million years at most, leading to the suggestion that the dark rings of Uranus are perhaps made of methane ice. The findings of Voyager 2 in the magnetosphere of Uranus are summarized in Fig. 9.[31] As the figure shows, the magnetic equatorial plasma sheet eventually becomes aligned in an antisolar direction at distances $\gtrsim 20$ Uranian radii from the planet. Uranus was also found to possess an extended hydrogen corona, as indicated in the figure, that may constitute a source of the plasma inside the magnetosphere. The Uranian moons do not appear to be a significant plasma source, contrary to the cases with Jupiter and Saturn, but act as absorbers of trapped particles, as shown in the figure. The radio emission of Uranus, although similar to that of Saturn in

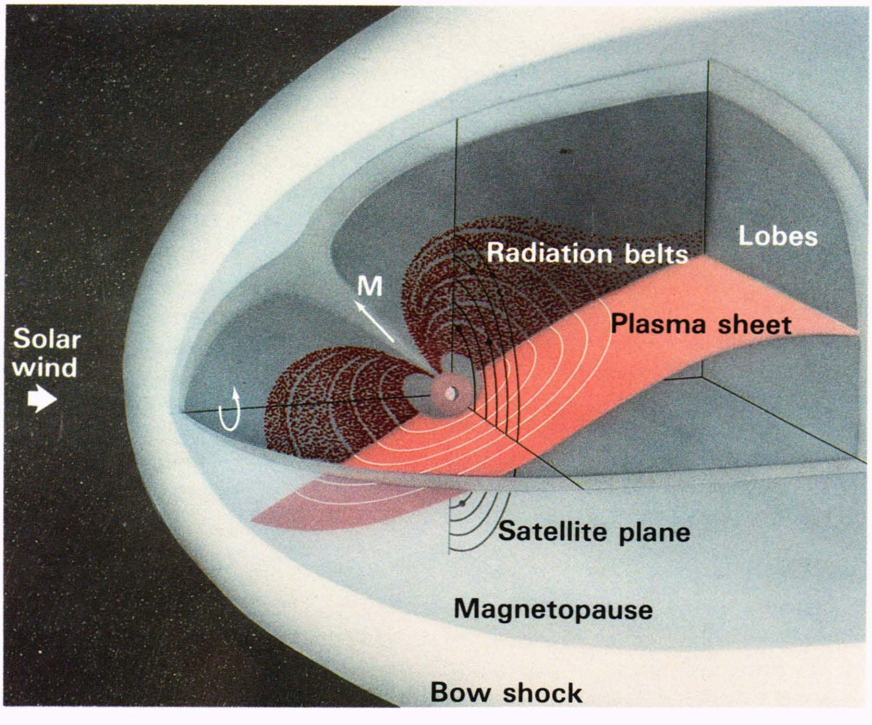

Figure 9—An overview sketch of the Uranian magnetosphere showing bow shock and magnetopause, boundary layer, dayside cusp, satellite plane, plasma sheet (shaded red), radiation belts, effects of satellite sweeping, and the extended hydrogen atmosphere around Uranus. The magnetic and rotation axes are marked. (From Ref. 31.)

spectral extent, is less in absolute power by about an order of magnitude, but yet is substantially more intense than that observed at Earth.

PLANETARY SATELLITES

Some of the satellites of Jupiter and Saturn could have magnetospheres. In particular, Io may have a tenuous atmosphere and an intrinsic magnetic field, which together could produce a smaller satellite magnetosphere as Jupiter's magnetosphere is swept past Io by Jupiter's rotation. Measurements thus far are insufficient to detect such a magnetosphere, to ascertain its nature, or to determine its importance in modulating Jovian radio emissions. The Voyager and Pioneer spacecraft have not returned evidence for magnetospheres around any of the Galilean satellites.

The best evidence for a magnetosphere within a magnetosphere[34] is from Saturn's satellite Titan, whose surface atmospheric pressure is about 1.6 times that of the Earth.[27] Voyager 1 found that Titan lacks an intrinsic magnetic field, but that its atmosphere and ionosphere form a cavity in the rotating Saturnian magnetosphere. This cavity forms through a mechanism similar to that by which the flowing solar wind induces a magnetosphere around Venus. Voyager 1 found that Titan has a magnetotail, somewhat tilted with respect to the plasma that rotates with Saturn; the flow of the plasma is disrupted across the magnetotail.

The dynamics of the Saturnian magnetosphere, as evidenced by the differences in the Voyager 1 and Voyager 2 encounters, should place Titan outside the magnetosphere for 30 to 50 percent of its orbit on average. Hence, the exact contribution of Titan's atmosphere to the particle population of Saturn's magnetosphere is uncertain. However, because Titan always passes through Saturn's magnetotail, it is safe to assume that it has a significant effect on the dynamics of the Saturnian magnetosphere, particularly on the nightside.

COMETARY MAGNETOSPHERES

The presence of cometary ion tails was used by Biermann[37] to infer the presence of the highly conducting gas emitted by the sun, the solar wind. Later, Alfvén[38] suggested the general configuration of the magnetic field and plasma environment during the interaction of a comet with the solar wind, including the pileup of magnetic field lines and the presence of a current sheet on the anti-Sunward side of the comet. These predictions were first tested by the release of gases (lithium and barium) in the solar wind during the recent Active Magnetospheric Particle Tracer Explorers project.[39,40] The presence of a diamagnetic cavity accompanied by a subsequent pileup of magnetic field lines and the equivalent of a bow shock wave were observed to have formed. In addition, the pickup of ions through the interplanetary electric field $[E = -1/c\,(\mathbf{V} \times \mathbf{B})]$ was seen and measured in detail.

In the recent past, spacecraft have encountered two comets, Giacobini-Zinner on September 11, 1985, and Halley's Comet in March 1986. The encounters basically confirmed several previous expectations but also produced a number of unexpected results. Figure 10 summarizes the findings obtained by the U.S International Cometary Explorer spacecraft in the first encounter with a comet.[41] The dark region with the extended tail in the diagram represents the visible part of the comet, as seen from Earth-based photographs. The spacecraft passed about 7800 kilometers behind the nucleus of the comet. The figure shows that the first detection of ion waves together with the presence of cometary ions occurred over 2 million kilometers from the nucleus. The ions had been cometary gases that became photoionized, picked up by the solar wind electric field, and accelerated to energies as high as 300 kiloelectronvolts for the heaviest species (most likely CO_2^+). At a distance of about 127,000 kilometers, the cometary bow shock was observed, as expected; closer to the nucleus (see inset), a turbulent region was identified where the solar wind had significantly slowed down due to "mass loading" from cometary ions. Inside a distance of about 8000 kilometers from the antisolar direction, a region of cold plasma was observed, accompanied by a general reduction in energetic ions and a minimum in the magnetic field magnitude resembling a diamagnetic cavity at the apparent crossing of a current sheet. The maximum magnetic field (draped) in the cometary tail lobes was about 60 nanoteslas.

The encounter of Halley's Comet in March 1986 by an international fleet of spacecraft[42] produced results similar to those obtained for Giacobini-Zinner. The Soviet Vega-1 and -2 spacecraft passed within a distance

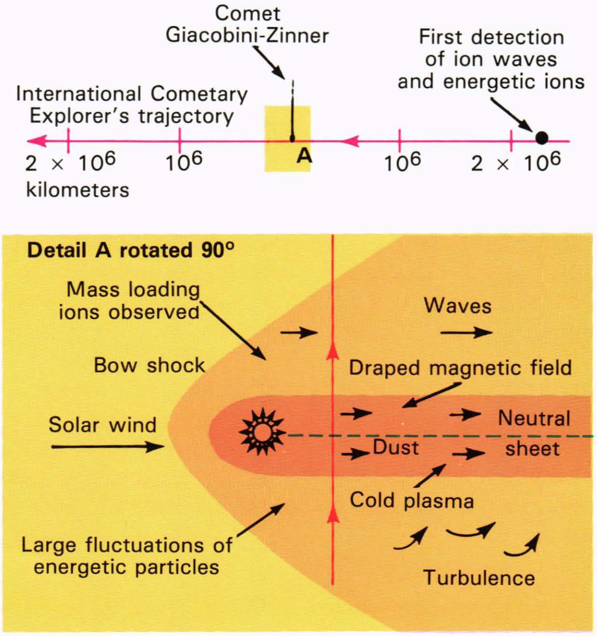

Figure 10—The first spacecraft encounter with a comet, on September 11, 1985. The International Cometary Explorer passed within 7800 kilometers behind the comet nucleus and obtained a wealth of information on the interaction of the hot flowing solar wind plasma with the cold cometary gas emitted by the comet. The various spatial regimes around the comet are noted in the inset. (Courtesy of J. K. Alexander, NASA.)

of about 8000 kilometers on the Sunward side of Halley, photographed its nucleus, observed its rotation period (about 53 hours), and determined a gas production rate of approximately 10^{30} molecules per second, with heavy ions such as C^+, CO_2^+, H_2O^+, and CH_4^+ clearly identified. Energetic ions to several hundred kiloelectronvolts were observed as far away as 10^7 kilometers from the comet nucleus. Similar findings were obtained by Japan's Planet A mission and the European Space Agency's Giotto spacecraft, which passed closest to the nucleus on the Sunward side at approximately 610 kilometers. As with the case of the International Cometary Explorer's encounter with Giacobini-Zinner, field-line draping and a cold plasma region were observed at Halley. The bow shock was observed to be farther away (about 4×10^5 kilometers) from the nucleus than with Giacobini-Zinner, due to the higher gas-production rate of Halley. The results obtained up to this time from the comet encounters are preliminary; further analyses will undoubtedly enhance our understanding of solar wind interaction with cometary objects.

THE FUTURE

There are possible magnetospheres in the solar system that we have yet to explore. The Voyager 2 spacecraft is on its way to Neptune for an encounter scheduled for August 24, 1989. The existence of a magnetosphere at Neptune will enhance considerably our understanding of the physics that underlies solar system magnetospheres. Unfortunately, it will not be possible to investigate the magnetosphere of Pluto in this century.

It is expected that within the next four years, the European Space Agency and the United States, in a joint project, will launch the first spacecraft to explore the high latitudes of the Sun's magnetosphere. This project, first called the Solar Polar Mission and then renamed Ulysses, will be the first to explore the Sun's polar region. By the turn of the century, we can expect to see exploration of the outer regions of the heliomagnetosphere, either by the Voyager and Pioneer spacecraft—which will be about 70 astronomical units from the Sun by that time—or by a proposed high-speed interstellar probe that will encounter the boundary of the heliomagnetosphere first, if that boundary is much beyond 70 astronomical units. Finally, to complete the picture, it is likely that a solar probe with a perihelion of approximately three solar radii will be launched before the end of the century to investigate the magnetosphere of the Sun close in. Data from the exploration of these magnetospheres will undoubtedly provide new insights into the interaction between magnetic fields and cold and hot plasmas.

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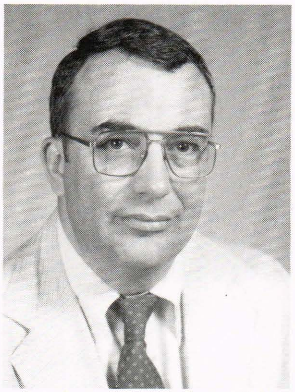

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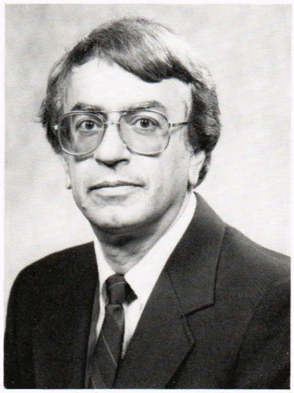

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