Planetary Magnetospheres

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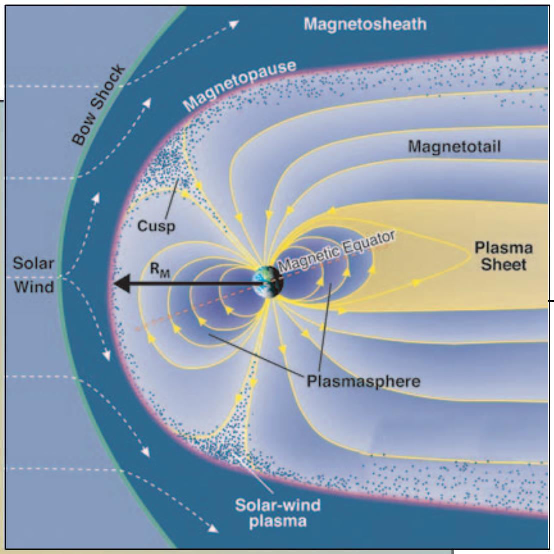


CHAPTER 28

1. What is a Magnetosphere?

The term **magnetosphere** was coined by T. Gold in 1959 to describe the region above the **ionosphere** in which the magnetic field of the Earth controls the motions of charged particles. The magnetic field traps low-energy plasma and forms the Van Allen belts, torus-shaped regions in which high-energy ions and electrons (tens of keV and higher) drift around the Earth. The control of charged particles by the planetary magnetic field extends many Earth radii into space but finally terminates near 10 Earth radii in the direction toward the Sun. At this distance, the magnetosphere is confined by a low-density, magnetized plasma called the **solar wind** that flows radially outward from the Sun at supersonic speeds. Qualitatively, a planetary magnetosphere is the volume of space from which the solar wind is excluded by a planet's magnetic field. (A schematic illustration of the terrestrial magnetosphere is given in Fig. 1, which shows how the solar wind is diverted around the magnetopause, a surface that surrounds the volume containing the Earth, its distorted magnetic field, and the plasma trapped within that field.) This qualitative definition is far from precise. Most of the time, solar wind plasma is not totally excluded from the region that we call the magnetosphere. Some solar wind plasma finds its way in and indeed many important dynamical phenomena give clear evidence of intermittent direct links between the solar wind and the plasmas governed by a planet's magnetic field. Moreover, unmagnetized planets in the flowing solar wind carve out cavities whose properties are sufficiently similar to those of true magnetospheres to allow us to include them in this discussion. Moons embedded in the flowing plasma of a planetary magnetosphere create interaction regions resembling those that surround unmagnetized planets. If a moon is sufficiently strongly magnetized, it may carve out a true magnetosphere completely contained within the magnetosphere of the planet.

Magnetospheric phenomena are of both theoretical and phenomenological interest. Theory has benefited from the data collected in the vast plasma laboratory of space in which different planetary environments provide the analogue of different laboratory conditions. Furthermore, magnetospheric plasma interactions are important to diverse elements of planetary science. For example, plasma trapped in a planetary magnetic field can interact strongly with the planet's atmosphere, heating the upper layers, generating neutral winds, ionizing the neutral gases and affecting the ionospheric flow. Energetic ions and electrons that precipitate into the atmosphere can modify atmospheric chemistry. Interaction with plasma particles can contribute to the isotopic fractionation of a planetary atmosphere over the lifetime of a planet. Impacts of energetic charged particles on the surfaces of planets and moons can modify surface properties, changing their albedos and spectral properties. The motions of charged dust grains in a planet's environment

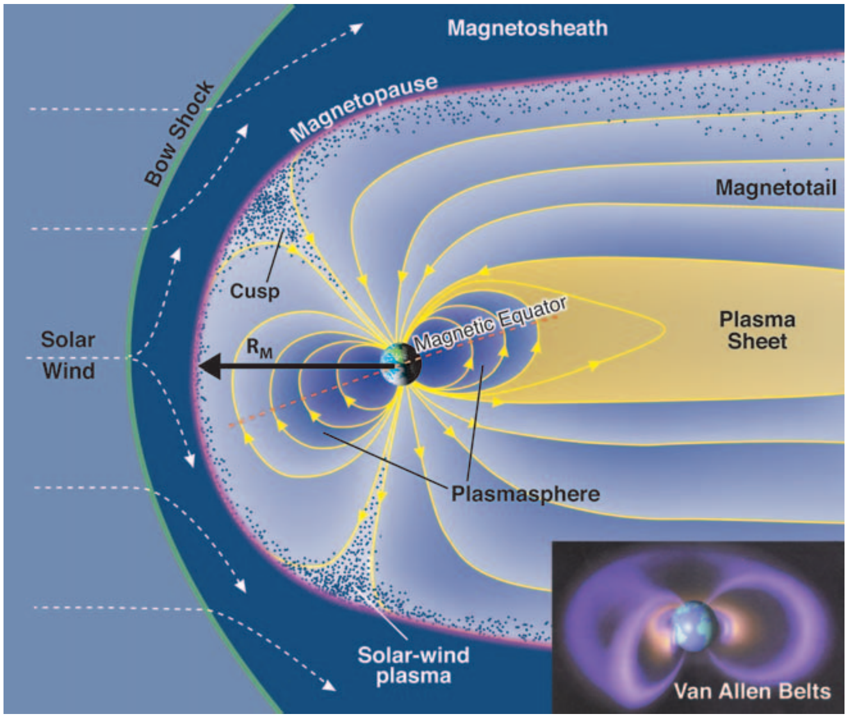


FIGURE 1 Schematic illustration of the Earth's magnetosphere. The Earth's magnetic field lines are shown as modified by the interaction with the solar wind. The solar wind, whose flow speed exceeds the speeds at which perturbations of the field and the plasma flow directions can propagate in the plasma, is incident from the left. The pressure exerted by the Earth's magnetic field excludes the solar wind. The boundary of the magnetospheric cavity is called the magnetopause, its nose distance being R_M. Sunward (upstream) of the magnetopause, a standing bow shock slows the incident flow, and the perturbed solar wind plasma between the bow shock and the magnetopause is called the magnetosheath. Antisunward (downstream) of the Earth, the magnetic field lines stretch out to form the magnetotail. In the northern portion of the magnetotail, field lines point generally sunward, while in the southern portion, the orientation reverses. These regions are referred to as the northern and southern lobes, and they are separated by a sheet of electrical current flowing generally dawn to dusk across the near-equatorial magnetotail in the plasmasheet. Low-energy plasma diffusing up from the ionosphere is found close to Earth in a region called the plasmasphere whose boundary is the plasmapause. The dots show the entry of magnetosheath plasma that originated in the solar wind into the magnetosphere, particularly in the polar cusp regions. Inset is a diagram showing the 3-dimensional structure of the Van Allen belts of energetic particles that are trapped in the magnetic field and drift around the Earth. [the New Solar System, (eds. Kelly Beatty et al.), CUP/Sky Publishing] Credit: Steve Bartlett; Inset: Don Davis.

are subject to both electrodynamic and gravitational forces; recent studies of dusty plasmas show that the former may be critical in determining the role and behavior of dust in the solar nebula as well as in the present-day solar system.

In Section 2, the different types of magnetospheres and related interaction regions are introduced. Section 3 presents the properties of observed planetary magnetic fields and discusses the mechanisms that produce such fields. Section 4 reviews the properties of plasmas contained within magnetospheres, describing their distribution, their sources, and some of the currents that they carry. Section 5 covers magnetospheric dynamics, both steady and "stormy." Section 6 addresses the interactions of moons with planetary plasmas. Section 7 concludes the chapter with remarks on plans for future space exploration.

2. Types of Magnetospheres

2.1 The Heliosphere

The solar system is dominated by the Sun, which forms its own magnetosphere referred to as the **heliosphere**. [*See* THE SUN.] The size and structure of the heliosphere are governed by the motion of the Sun relative to the local interstellar medium, the density of the interstellar plasma, and the pressure exerted on its surroundings by the outflowing solar wind that originates in the solar corona. [*See* THE SOLAR WIND.] The corona is a highly ionized gas, so hot that it can escape the Sun's immense gravitational field and flow outward at supersonic speeds. Through much of the heliosphere, the solar wind speed is not only supersonic but also much greater than the **Alfvén speed** ($v_A = B/(\mu_0 \rho)^{1/2}$), the speed at which rotational perturbations of the magnetic field propagate along the magnetic field in a magnetized plasma. (Here B is the magnetic field magnitude, μ_0 is the magnetic permeability of vacuum, and ρ is the mass density of the plasma.)

The solar wind is threaded by magnetic field lines that map back to the Sun. A useful and picturesque description of the field contained within a plasma relies on the idea that if the conductivity of a plasma is sufficiently large, the magnetic field is frozen into the plasma and field lines can be traced from their source by following the motion of the plasma to which it is frozen. Because the roots of the field lines remain linked to the rotating sun (the sun rotates about its axis with a period of approximately 25 days), the field lines twist in the form of an Archimedean spiral as illustrated in Fig. 2. The outflow of the solar wind flow along the direction of the Sun's motion relative to the interstellar plasma is terminated by the forces exerted by the interstellar plasma. Elsewhere the flow is diverted within the boundary of the heliosphere. Thus, the Sun and the solar wind are (largely) confined within the heliospheric cavity; the heliosphere is the biggest of the solar system magnetospheres.

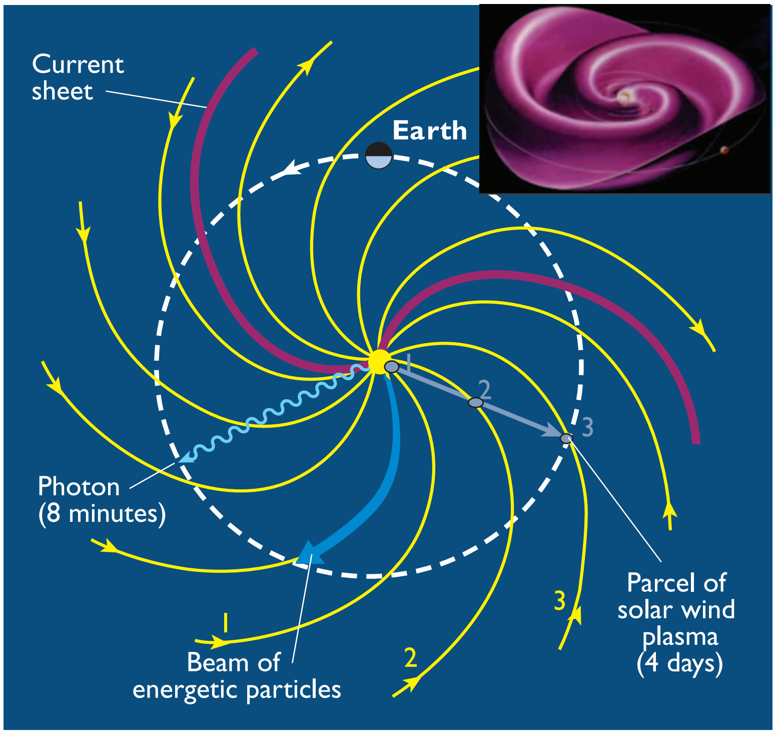


FIGURE 2 The magnetic field of the Sun is carried by the solar wind away from the Sun and is wound into a spiral. The heliospheric current sheet (colored magenta in the inset 3-dimensional diagram) separates magnetic fields of opposite polarities and is warped into a "ballerina skirt" by combined effects of the Sun's spin and the tilt of the magnetic field. The main diagram (2-dimensional projection) shows a cut through the heliosphere in the ecliptic plane. In the ecliptic plane, the radial flow of the solar wind and the rotation of the Sun combine to wind the solar magnetic field (yellow lines) into a spiral. A parcel of solar wind plasma (traveling radially at an average speed of 400 km/s) takes about 4 days to travel from the Sun to Earth's orbit at 1 AU. The dots and magnetic field lines labeled 1, 2, and 3 represent snapshots during this journey. Energetic particles emitted from the Sun travel much faster (beamed along the magnetic field) reaching the Earth in minutes to hours. Traveling at the speed of light, solar photons reach the Earth in 8 minutes. Credit: J. A. Van Allen and F. Bagenal, 1999, Planetary magnetospheres and the interplanetary medium, in "The New Solar System," 4th Ed. (Beatty, Petersen, and Chaikin, eds.), Sky Publishing and Cambridge Univ. Press.

Our knowledge of the heliosphere beyond the orbits of the giant planets was for decades principally theoretical, but data acquired by *Voyager 1* and *2* since their last planetary encounters in 1989 have provided important evidence of the structure of the outer heliosphere. The solar wind density continues to decrease as the inverse square of the distance from the Sun; as the plasma becomes sufficiently tenuous, the pressure of the interstellar plasma impedes its further expansion. The solar wind slows down abruptly across a shock (referred to as the termination shock) before reaching the **heliopause,** the boundary that separates the solar wind from the interstellar plasma. (The different plasma regimes are schematically illustrated in Fig. 3.)

Voyager 1 encountered the termination shock on December 16, 2004, at a distance of 94 AU (AU is an astronomical unit, equal to the mean radius of Earth's orbit or about 1.5 × 10^8 km) from the Sun and entered the heliosheath, the boundary layer between the termination shock and the heliopause. The encounter with the termination shock had long been anticipated as an opportunity to identify the processes that accelerate a distinct class of cosmic rays, referred to as anomalous cosmic rays (ACRs). ACRs are extremely energetic, singly charged ions (energies of the order of 10 MeV/nucleon) produced by ionization of interstellar neutrals. The mechanism that accelerates them to high energy is not established. Some models propose that these particles are ionized and accelerated near the termination shock, but the *Voyager* data show no sign of a change in the energy spectrum or the intensity of the flux across the termination shock; thus, the acceleration mechanism remains a mystery.

Various sorts of electromagnetic waves and plasma waves have been interpreted as coming from the termination shock or the heliopause. Bursts of radio emissions that do not weaken with distance from known sources within the solar systems were observed intermittently by *Voyager* between 1983 and 2004. They are thought to be emissions generated when an interplanetary shock propagating outward from the Sun reaches the heliopause. Plasma waves driven by electron beams generated at the termination

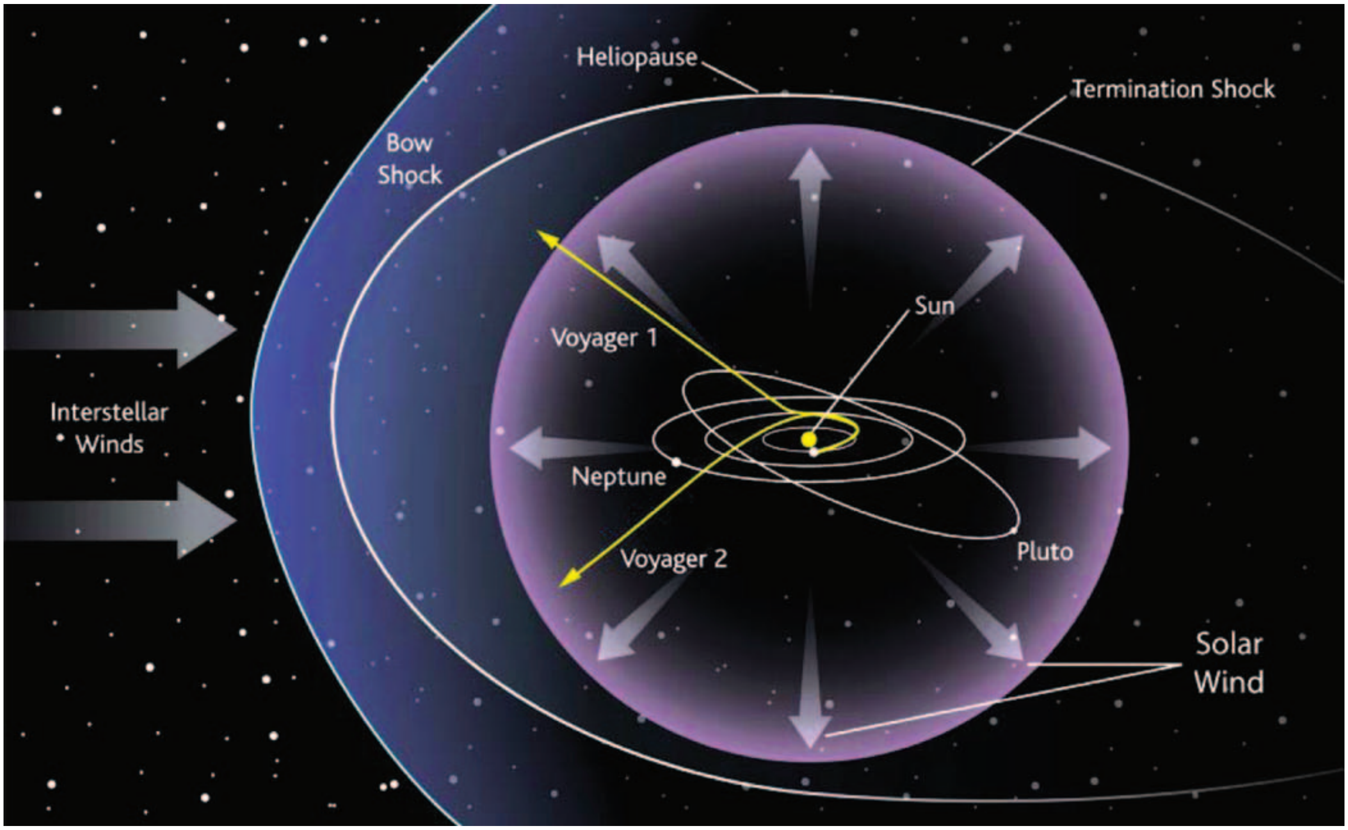


FIGURE 3 Schematic illustration of the heliosphere. The direction of plasma in the local interstellar medium relative to the Sun is indicated, and the boundary between solar wind plasma and interstellar plasma is identified as the heliopause. A broad internal shock, referred to as the termination shock, is shown within the heliopause. Such a shock, needed to slow the outflow of the supersonic solar wind inside of the heliopause, is a new feature in this type of magnetosphere. Beyond the heliopause, the interstellar flow is diverted around the heliosphere and a shock that slows and diverts flow probably exists. Credit: L. A. Fisk, 2005, Journey into the unknown beyond, *Science* **2016** (September 23), 309, www.sciencemag.org.

TABLE 1 **Properties of the Solar Wind and Scales of Planetary Magnetospheres**

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Distance, a_{planet} (AU)[a]	0.31–0.47	0.723	1[b]	1.524	5.2	9.5	19	30	30–50
Solar wind density (amu cm^{-3})[b]	35–80	16	8	3.5	0.3	0.1	0.02	0.008	0.008–0.003
Radius, R_P (km)	2,439	6,051	6,373	3,390	71,398	60,330	25,559	24,764	1,170 (±33)
Surface magnetic field, B_0 (Gauss = 10^{-4} T)	3×10^{-3}	$<2 \times 10^{-5}$	0.31	$<10^{-4}$	4.28	0.22	0.23	0.14	?
R_{MP} (R_{Planet})	1.4–1.6 R_M	—	10 R_E	—	42 R_J	19 R_S	25 R_U	24 R_N	
Observed size of magnetosphere (km)	1.4 R_M 3.6×10^3	— —	8–12 R_E 7×10^4	— —	50–100 R_J 7×10^6	16–22 R_S 1×10^6	18 R_U 5×10^5	23–26 R_N 6×10^5	?

[a] 1 AU = 1.5×10^8 km.

[b] The density of the solar wind fluctuates by about a factor of 5 about typical values of $\rho_{sw} \sim [(8 \text{ amu cm}^{-3})/a^2_{\text{planet}}]$.

[c] Magnetopause nose distance, R_{MP} is calculated using $R_{MP} = (B_0^2/2\mu_0 \rho u^2)^{1/6}$ for typical solar wind conditions of ρ_{sw} given above and $u \sim 400$ km s^{-1}. For outer planet magnetospheres, this is usually an underestimate of the actual distance.

shock and propagating inward along the spiral field lines of the solar wind have also been identified. As *Voyager* continues its journey out of the solar system, it should encounter the heliopause and enter the shocked interstellar plasma beyond. One can predict that new surprises await discovery.

2.2 Magnetospheres of the Unmagnetized Planets

Earth has a planetary magnetic field that has long been used as a guide by such travelers as scouts and sea voyagers. However, not all of the planets are magnetized. Table 1 summarizes some key properties of some of the planets including their surface magnetic field strengths. The planetary magnetic field of Mars is extremely small, and the planetary magnetic field of Venus is nonexistent. [*See* MARS and VENUS: SURFACE AND INTERIOR.] The nature of the interaction between an unmagnetized planet and the supersonic solar wind is determined principally by the electrical conductivity of the body. If conducting paths exist across the planet's interior or ionosphere, then electric currents flow through the body and into the solar wind where they create forces that slow and divert the incident flow. The diverted solar wind flows around a region that is similar to a planetary magnetosphere. Mars and Venus have ionospheres that provide the required conducting paths The barrier that separates planetary plasma from solar wind plasma is referred to as an **ionopause.** The analogous boundary of the magnetosphere of a magnetized planet is called a magnetopause. Earth's Moon, with no ionosphere and a very low conductivity surface, does not deflect the bulk of the solar wind incident on it. Instead, the solar wind runs directly into the surface, where it is absorbed. [*See* THE MOON.] The absorption leaves the region immediately downstream of the Moon in the flowing plasma (the wake) devoid of plasma, but the void fills in as solar wind plasma flows toward the center of the wake. The different types of interaction are illustrated in Fig. 4.

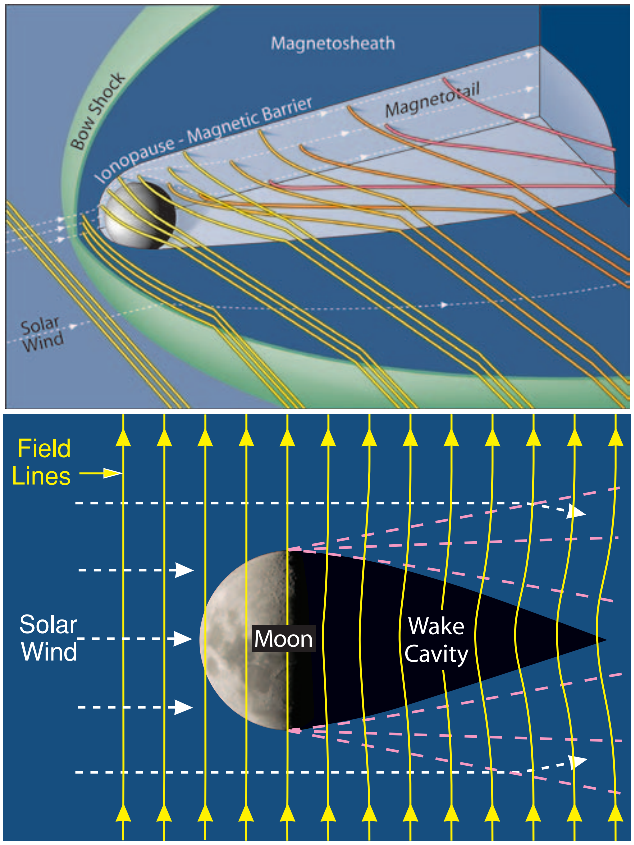


FIGURE 4 Schematic illustrations of the interaction regions surrounding, top, a planet like Mars or Venus, which is sufficiently conducting that currents close through the planet or its ionosphere (solar magnetic field lines are shown in yellow to red and are draped behind the planet) and, bottom, a body like the Moon, which has no ionosphere and low surface and interior conductivity. Credit: Steve Bartlett.

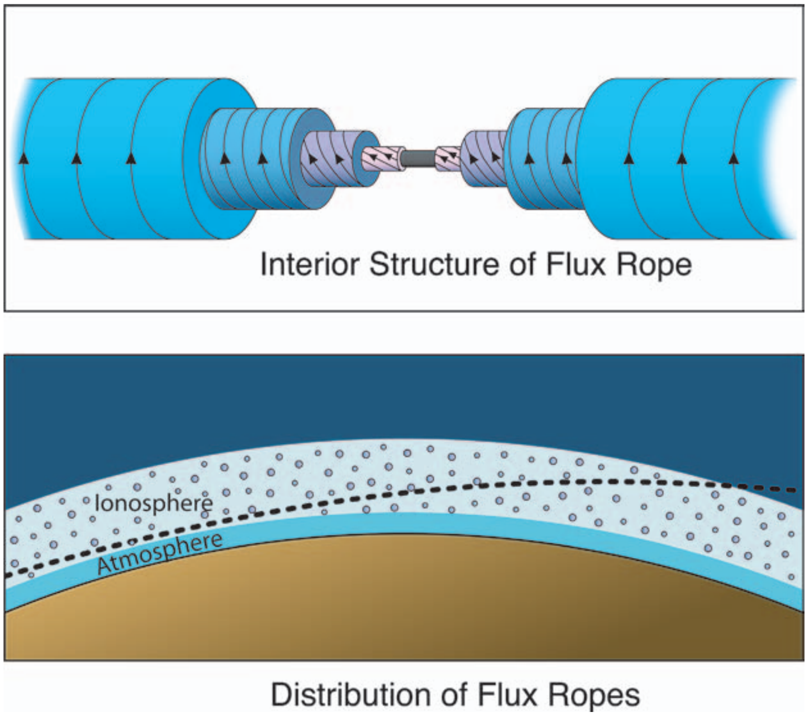


FIGURE 5 Schematic illustration of a flux rope, a magnetic structure that has been identified in the ionosphere of Venus (shown as black dots within the ionosphere) and extensively investigated (a low-altitude pass of the *Pioneer Venus Orbiter* is indicated by the dashed curve). The rope (see above) has an axis aligned with the direction of the central field. Radially away from the center, the field wraps around the axis, its helicity increasing with radial distance from the axis of the rope. Structures of this sort are also found in the solar corona and in the magnetotails of magnetized planets. Credit: Steve Bartlett.

The magnetic structure surrounding Mars and Venus has features much like those found in a true magnetosphere surrounding a strongly magnetized planet. This is because the interaction causes the magnetic field of the solar wind to drape around the planet. The draped field stretches out downstream (away from the Sun), forming a magnetotail. The symmetry of the magnetic configuration within such a tail is governed by the orientation of the magnetic field in the incident solar wind, and that orientation changes with time. For example, if the interplanetary magnetic field (IMF) is oriented northward, the east–west direction lies in the symmetry plane of the tail and the northern lobe field (see Fig. 1 for the definition of lobe) points away from the Sun, while the southern lobe field points toward the Sun. A southward-oriented IMF would reverse these polarities, and other orientations would produce rotations of the symmetry axis.

Much attention has been paid to magnetic structures that form in and around the ionospheres of unmagnetized planets. Magnetic flux tubes of solar wind origin pile up at high altitudes at the day side ionopause where, depending on the solar wind dynamic pressure, they may either remain for extended times, thus producing a magnetic barrier that diverts the incident solar wind, or penetrate to low altitudes in localized bundles. Such localized bundles of magnetic flux are often highly twisted structures stretched out along the direction of the magnetic field. Such structures, referred to as flux ropes, are illustrated in Fig. 5.

Although Mars has only a small global scale magnetic field and interacts with the solar wind principally through currents that link to the ionosphere, there are portions of the surface over which local magnetic fields block the access of the solar wind to low altitudes. It has been suggested that "mini-magnetospheres" extending up to 1000 km form above the regions of intense crustal magnetization in the southern hemisphere; these mini-magnetospheres protect portions of the atmosphere from direct interaction with the solar wind. As a result, the crustal magnetization may have modified the evolution of the atmosphere and may still contribute to the energetics of the upper atmosphere.

2.3 Interactions of the Solar Wind with Asteroids, Comets and Pluto

Asteroids are small bodies (<1000 km radius and more often only tens of kilometers) whose signatures in the solar wind were first observed by the *Galileo* spacecraft in the early 1990s. [*See* MAIN-BELT ASTEROIDS.] Asteroid-related disturbances are closely confined to the regions near to and downstream of the magnetic field lines that pass through the body, and thus the interaction region is fan-shaped as illustrated in Fig. 6 rather than bullet-shaped like Earth's magnetosphere. Unlike Earth's magnetosphere, there is no shock standing ahead of the disturbance in the solar wind. The signature found by *Galileo* in the vicinity of the asteroid Gaspra suggested that the asteroid is magnetized at a level similar to the magnetization of meteorites. Because the measurement locations were remote from the body, its field was not measured directly, and it is possible that the putative magnetic signature was a fortuitous rotation of the interplanetary magnetic field. Data from other asteroids do not establish unambiguously the strength of their magnetic

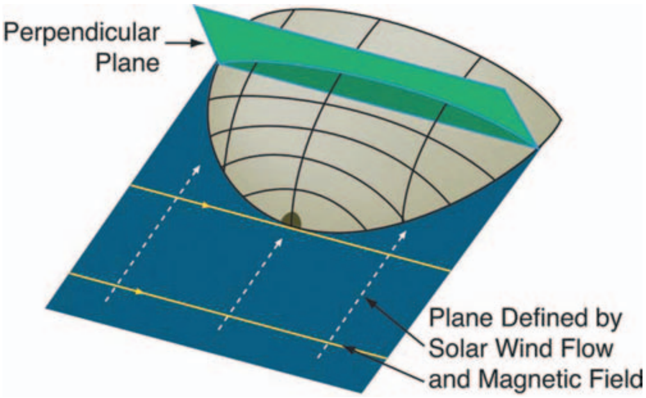


FIGURE 6 Schematic of the shape of the interaction between an asteroid and the flowing solar wind. The disturbance spreads out along the direction of the magnetic field downstream of the asteroid. The disturbed region is thus fan-shaped, with greatest spread in the plane defined by the solar wind velocity and the solar wind magnetic field. The curves bounding the intersection of that plane with the surface and with a perpendicular plane are shown. Credit: Steve Bartlett.

fields. A negligibly small magnetic field was measured by the *NEAR–Shoemaker* mission close to and on the surface of asteroid Eros, possibly because it is formed of magnetized rocks of random orientation. Although there will be no magnetometer on the *DAWN* spacecraft that will make measurements at Ceres and Vesta, other missions under discussion would add to our knowledge of asteroid magnetic properties. We may some day have better determinations of asteroidal magnetic fields and be able to establish how they interact with the solar wind.

Comets are also small bodies. The spectacular appearance of an active comet, which can produce a glow over a large visual field extending millions of kilometers in space on its approach to the Sun, is somewhat misleading because comet nuclei are no more than tens of kilometers in diameter. It is the gas and dust released from these small bodies by solar heating that we see spread out across the sky. Some of the gas released by the comet remains electrically neutral, with its motion governed by purely mechanical laws, but some of the neutral matter becomes ionized either by photoionization or by exchanging charge with ions of the solar wind. The newly ionized cometary material is organized in interesting ways that have been revealed by spacecraft measurements in the near neighborhood of comets Halley, Giacobini–Zinner, and Borrelly. Figure 7 shows schematically the types of regions that have been identified. Of particular interest is that the different gaseous regions fill volumes of space many orders of magnitude larger than the actual solid comet. The solar wind approaching the comet first encounters the expanding neutral gases blown off the comet. As the neutrals are ionized by solar photons, they extract momentum from the solar wind, and the flow slows a bit. Passing through a shock that further decelerates the flow, the solar wind encounters ever-increasing densities of newly ionized gas of cometary origin, referred to as pickup ions. Energy is extracted from the solar wind as the pickup ions are swept up, and the flow slows further. Still closer to the comet, in a region referred to as the cometopause, a transition in composition occurs as the pickup ions of cometary origin begin to dominate the plasma composition. Close to the comet, at the **contact surface,** ions flowing away from the comet carry enough momentum to stop the flow of the incident solar wind. Significant asymmetry of the plasma distribution in the vicinity of a comet may arise if strong collimated jets of gas are emitted by the cometary nucleus. Such jets have been observed at Halley's comet and at comet Borrelly.

Pluto is also a small body even though it has been classified as a planet (until 2006). Pluto's interaction with the solar wind has not yet been observed, but it is worth speculating about what that interaction will be like in order to test our understanding of comparative planetology. [*See* PLUTO.] The solar wind becomes tenuous and easily perturbed at large distances from the Sun (near 30 AU), and either escaping gases or a weak internal magnetic field could produce an interaction region many times Pluto's size. At some phases of its 248-year orbital period, Pluto moves close enough to the Sun for its surface ice to sublimate, producing an atmosphere and possibly an ionosphere. Models of Pluto's atmosphere suggest that the gases would then escape and flow away from the planet. If the escape flux is high, the solar wind interaction would then appear more like a comet than like Venus or Mars. Simulations show a very asymmetric shock surrounding the interaction region for a small but possible neutral escape rate. Pluto's moon, Charon, may serve as a plasma source within the magnetosphere, and this could have interesting consequences of the type addressed in Section 6 in relation to the moons of Jupiter and Saturn. As is the case for small asteroids and comets, ions picked up in the solar wind at Pluto have **gyroradii** and ion inertial lengths that are large compared with the size of the obstacle, a situation that adds asymmetry and additional complexity to the interaction. For most of its orbital period, Pluto is so far from the Sun that its interaction with the solar wind is more likely to resemble that of the Moon, with absorption occurring at the sunward surface and a void developing in its wake. It seems unlikely that a small icy body will have an internal magnetic field large enough to produce a magnetospheric interaction region, but one must recognize that actual observations of the magnetic fields of small bodies have repeatedly challenged our ideas about magnetic field generation.

2.4 Magnetospheres of Magnetized Planets

In a true magnetosphere, the scale size is set by the distance, R_{MP}, along the planet–Sun line at which the sum of the pressure of the planetary magnetic field and the pressure exerted by plasma confined within that field balance the dynamic pressure of the solar wind. (The dynamic pressure

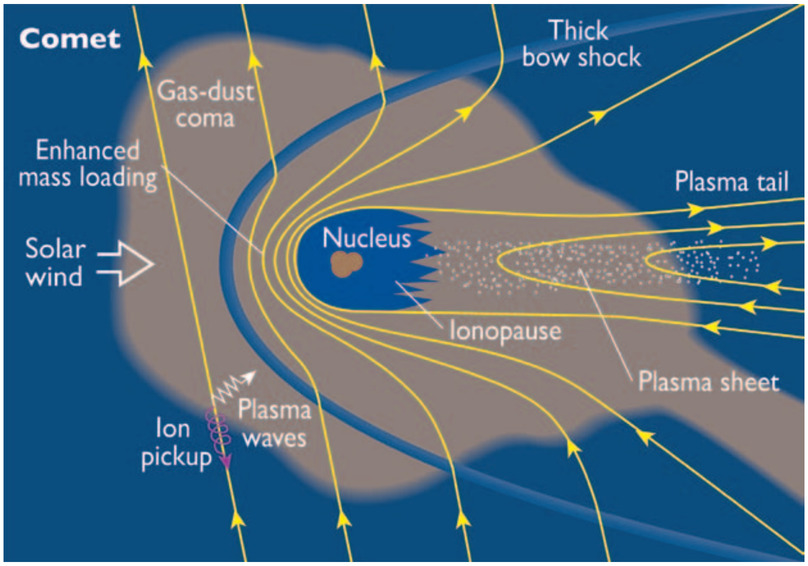


FIGURE 7 Schematic illustration of the magnetic field and plasma properties in the neighborhood of a comet. The length scale is logarithmic. The nucleus is surrounded by a region of dense plasma into which the solar wind does not penetrate. This region is bounded by a contact surface. Above that lies an ionopause or cometopause bounding a region in which ions of cometary origin dominate. Above this, there is a transition region in which the solar wind has been modified by the addition of cometary ions. As ions are added, they must be accelerated to become part of the flow. The momentum to accelerate the picked-up ions is extracted from the solar wind; consequently, in the transition region, the density is higher and the flow speed is lower than in the unperturbed solar wind. The newly picked up ions often generate plasma waves. The region filled with cometary material is very large, and it is this region that imposes the large-scale size on the visually observable signature of a comet. Spacecraft observations suggest that there is no shock bounding the cometary interaction region because the effects of ion pickup serve to slow the flow below the critical sound and Alfvén speeds without the need for a shock transition. Similar to Venus-like planets, the solar wind magnetic field folds around the ionopause, producing a magnetic tail that organizes the ionized plasma in the direction radially away from the Sun and produces a distinct comet tail with a visual signature. The orientation of the magnetic field in the tail is governed by the solar wind field incident on the comet, and it changes as the solar wind field changes direction. Dramatic changes in the structure of the magnetic tail are observed when the solar wind field reverses direction. Credit: J. A. Van Allen and F. Bagenal, 1999, Planetary magnetospheres and the interplanetary medium, in "The New Solar System," 4th Ed. (Beatty, Petersen, and Chaikin, eds.), Sky Publishing and Cambridge Univ. Press.

is ρu^2 where ρ is the mass density and u is its flow velocity in the rest frame of the planet. The thermal and magnetic pressures of the solar wind are small compared with its dynamic pressure.) Assuming that the planetary magnetic field is dominated by its dipole moment and that the plasma pressure within the magnetosphere is small, one can estimate R_{MP} as $R_{\mathrm{MP}} \approx R_{\mathrm{P}}(B_0{}^2/2\mu_0\rho u^2)^{1/6}$. Here B_0 is the surface equatorial field of the planet and R_{P} is its radius. Table 1 gives the size of the magnetosphere, R_{MP}, for the different planets and shows the vast range of scale sizes both in terms of the planetary radii and of absolute distance.

Within a magnetosphere, the magnetic field differs greatly from what it would be if the planet were placed in a vacuum. The field is distorted, as illustrated in Fig. 1, by currents carried on the magnetopause and in the plasma trapped within the magnetosphere. Properties of the trapped plasma and its sources are discussed in Section 4. An important source of magnetospheric plasma is the solar wind. Figure 1 makes it clear that, along most of the boundary, solar wind plasma would have to move across magnetic field lines to enter the magnetosphere. The **Lorentz force** of the magnetic field opposes such motion. However, shocked solar wind plasma of the magnetosheath easily penetrates the boundary by moving along the field in the polar cusp. Other processes that enable solar wind plasma to penetrate the boundary are discussed in Section 5.

3. Planetary Magnetic Fields

Because the characteristic time scale for **thermal diffusion** is greater than the age of the solar system, the planets tend to have retained their heat of formation. At the same time, the characteristic time scale for diffusive decay of a magnetic field in a planetary interior is much less than the age of the planets. Consequently, primordial fields and permanent magnetism on a planetary scale are small and the only means of providing a substantial planetary magnetic field is an internal dynamo. For a planet to have a magnetic dynamo, it must have a large region that is fluid, electrically conducting and undergoing convective motion. The deep interiors of the planets and many larger satellites are expected to contain electrically conducting fluids: terrestrial planets and the larger satellites have differentiated cores of liquid iron alloys; at the high pressures in the interiors of the giant planets Jupiter and Saturn, hydrogen behaves like a liquid metal; for Uranus and Neptune, a water–ammonia–methane mixture forms a deep conducting "ocean." [*See* INTERIORS OF THE GIANT PLANETS.] The fact that some planets and satellites do not have dynamos tells us that their interiors are stably stratified and do not convect or that the interiors have solidified. Models of the thermal evolution of terrestrial planets show that as the object cools, the liquid core ceases to convect, and further heat is lost by conduction alone. In some cases, such as the Earth, convection continues because the nearly pure iron solidifies out of the alloy in the outer core, producing an inner solid core and creating compositional gradients that drive convection in the liquid outer core. The more gradual cooling of the giant planets also allows convective motions to persist.

Of the eight planets, six are known to generate magnetic fields in their interiors. Exploration of Venus has provided an upper limit to the degree of magnetization comparable to the crustal magnetization of the Earth suggesting that its core is stably stratified and that it does not have an active dynamo. The question of whether Mars does or does not have a weak internal magnetic field was disputed for many years because spacecraft magnetometers had measured the field only far above the planet's surface. The first low-altitude magnetic field measurements were made by *Mars Global Surveyor* in 1997. It is now known that the surface magnetic field of Mars is very small ($|\mathbf{B}| < 10$ nT or 1/3000 of Earth's equatorial surface field) over most of the northern hemisphere but that in the southern hemisphere there are extensive regions of intense crustal magnetization as already noted. Pluto has yet to be explored. Models of Pluto's interior suggest it is probably differentiated, but its small size makes one doubt that its core is convecting and any magnetization is likely to be remanent. Earth's moon has a negligibly small planet-scale magnetic field, though localized regions of the surface are highly magnetized. Jupiter's large moons are discussed in Section 6.

The characteristics of the six known planetary fields are listed in Table 2. Assuming that each planet's magnetic field has the simplest structure, a dipole, we can characterize the magnetic properties by noting the equatorial field strength (B_0) and the tilt of the axis with respect to the planet's spin axis. For all the magnetized planets other than Mercury, the surface fields are on the order of a Gauss $= 10^{-4}$ T, meaning

TABLE 2 Planetary Magnetic Fields

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
Magnetic moment, (M_{Earth})	4×10^{-4}	1[a]	20,000	600	50	25
Surface magnetic field						
At dipole equator (Gauss)	0.0033	0.31	4.28	0.22	0.23	0.14
Maximum/minimum[b]	2	2.8	4.5	4.6	12	9
Dipole tilt and sense[c]	+14°	+10.8°	−9.6°	−0.0°	−59°	−47°
Obliquity[d]	0°	23.5°	3.1°	26.7°	97.9°	29.6°
Solar wind angle[e]	90°	67–114°	87–93°	64–117°	8–172°	60–120°

[a] $M_{\mathrm{Earth}} = 7.906 \times 10^{25}$ Gauss cm^3 $= 7.906 \times 10^{15}$ Tesla m^3.

[b] Ratio of maximum surface field to minimum (equal to 2 for a centered dipole field).

[c] Angle between the magnetic and rotation axes.

[d] The inclination of the equator to the orbit.

[e] Range of angle between the radial direction from the Sun and the planet's rotation axis over an orbital period.

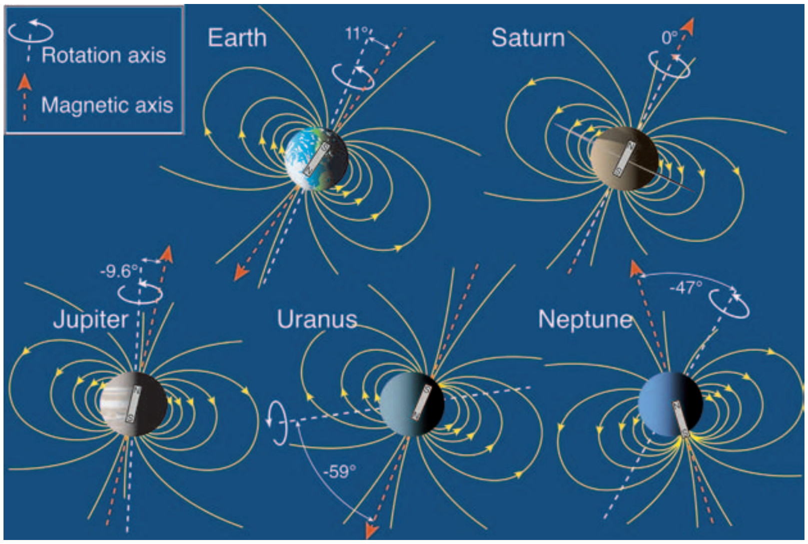


FIGURE 8 Orientation of the planets' spin axes and their magnetic fields (magnetic field lines shown in yellow) with respect to the ecliptic plane (horizontal). The larger the angle between these two axes, the greater the magnetospheric variability over the planet's rotation period. The variation in the angle between the direction of the solar wind (close to radial from the Sun) and a planet's spin axis over an orbital period is an indication of the degree of seasonal variability. Credit: Steve Bartlett.

that their dipole moments are of order $4\pi\mu_o{}^{-1}R_p{}^3\,10^{-4}$ T, where R_p is the planetary radius (i.e., the dipole moments scale with planetary size). The degree to which the dipole model is an oversimplification of more complex structure is indicated by the ratio of maximum to minimum values of the surface field. This ratio has a value of 2 for a dipole. The larger values, particularly for Uranus and Neptune, are indications of strong nondipolar contributions to the planets' magnetic fields. Similarly, the fact that the magnetic axes of these two planets are strongly tilted (see Fig. 8) also suggests that the dynamos in the icy giant planets may be significantly different than those of the planets with aligned, dipolar planetary magnetic fields.

The size of a planet's magnetosphere (R_{MP}) depends not only on the planet's radius and magnetic field but also on the ambient solar wind density, which decreases as the inverse square of the distance from the Sun. (The solar wind speed is approximately constant with distance from the Sun.) Thus, it is not only planets with strong magnetic fields that have large magnetospheres but also the planets Uranus and Neptune whose weak magnetic fields create moderately large magnetospheres in the tenuous solar wind far from the Sun. Table 1 shows that the measured sizes of planetary magnetospheres generally agree quite well with the theoretical R_{MP} values. Jupiter, where the plasma pressure inside the magnetosphere is sufficient to further "inflate" the magnetosphere, is the only notable exception. The combination of a strong internal field and relatively low solar wind density at 5 AU makes the magnetosphere of Jupiter a huge object—about 1000 times the volume of the Sun, with a tail that extends at least 6 A.U. in the antisunward direction, beyond the orbit of Saturn. If the jovian magnetosphere were visible from Earth, its angular size would be much larger than the size of the Sun, even though it is at least 4 times farther away. The magnetospheres of the other giant planets are smaller (although large compared with the Earth's magnetosphere), having similar scales of about 20 times the planetary radius, comparable to the size of the Sun. Mercury's magnetosphere is extremely small because the planet's magnetic field is weak and the solar wind close to the Sun is very dense. Figure 9 compares the sizes of several planetary magnetospheres.

Although the size of a planetary magnetosphere depends on the strength of a planet's magnetic field, the configuration and internal dynamics depend on the field orientation (illustrated in Fig. 8). At a fixed phase of planetary rotation, such as when the dipole tilts toward the Sun, the orientation of a planet's magnetic field is described by two angles (tabulated in Table 2): the tilt of the magnetic field with respect to the planet's spin axis and the angle between the planet's spin axis and the solar wind direction, which is generally within a few degrees of being radially outward from the Sun. Because the direction of the spin axis with respect to the solar wind direction varies only over a planetary year (many Earth years for the outer planets), and the planet's magnetic field is assumed to vary only on geological time scales, these two angles are constant for the purposes of describing the magnetospheric configuration at a particular epoch. Earth, Jupiter and Saturn have small dipole tilts and small obliquities. This means that changes of the orientation of the magnetic field with respect to the solar wind over a planetary rotation period and seasonal effects, though detectable, are small. Thus, Mercury, Earth, Jupiter, and Saturn have reasonably symmetric, quasi-stationary magnetospheres, with the first three exhibiting a small wobble at the planetary rotation period owing to their ~10° dipole tilts. In contrast, the large dipole tilt angles of Uranus and Neptune imply that the orientation of their magnetic fields with respect to the interplanetary flow direction varies greatly over a planetary rotation period, resulting in highly asymmetric

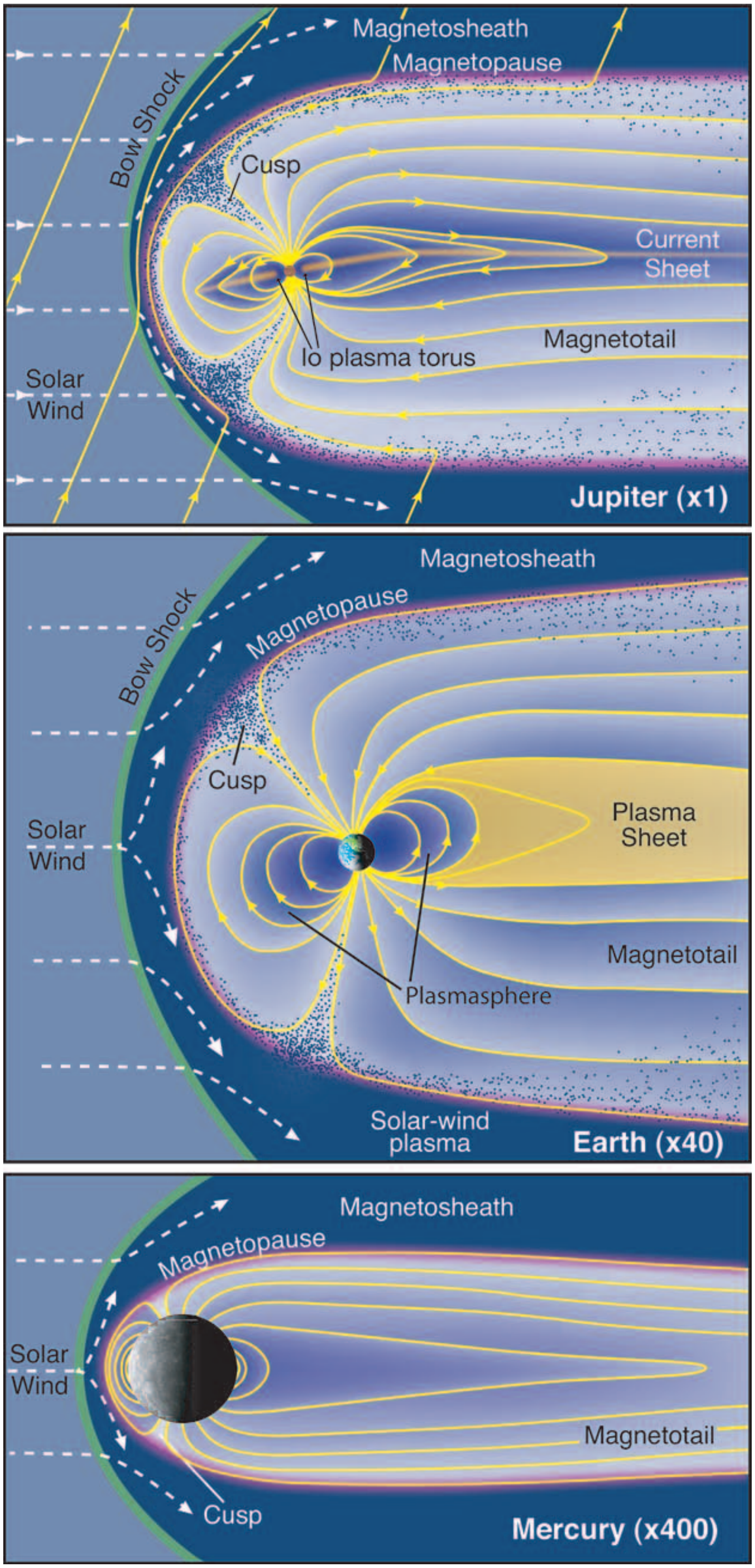


FIGURE 9 Schematic comparison of the magnetospheres of Jupiter, Earth, and Mercury. Relative to the Jupiter schematic, the one for Earth is blown up by a factor of 40, and the one for Mercury is blown up by a factor of 400. The planetary radii are given in Table 1. Credit: Steve Bartlett.

magnetospheres that vary at the period of planetary rotation. Furthermore, Uranus' large obliquity means that the magnetospheric configuration will undergo strong seasonal changes over its 84-year orbit.

4. Magnetospheric Plasmas

4.1 Sources of Magnetospheric Plasmas

Magnetospheres contain considerable amounts of plasma, electrically charged particles in equal proportions of positive charge on ions and negative charge on electrons, from various sources. The main source of plasma in the solar system is the Sun. The solar corona, the upper atmosphere of the Sun (which has been heated to temperatures of 1–2 million Kelvin), streams away from the Sun at a more or less steady rate of 10^9 kg s^{-1} in equal numbers (8×10^{35} s^{-1}) of electrons and ions. The boundary between the solar wind and a planet's magnetosphere, the magnetopause, is not entirely plasma-tight. Wherever the interplanetary magnetic field has a component antiparallel to the planetary magnetic field near the magnetopause boundary, magnetic **reconnection** (discussed in Section 5) is likely to occur, and solar wind plasma can enter the magnetosphere across the magnetopause. Solar wind material is identified in the magnetosphere by its energy and characteristic composition of protons (H^+) with ~4% alpha particles (He^{2+}) and trace heavy ions, many of which are highly ionized.

A secondary source of plasma is the ionosphere. Although ionospheric plasma is generally cold and gravitationally bound to the planet, a small fraction can acquire sufficient energy to escape up magnetic field lines and into the magnetosphere. In some cases, field-aligned potential drops accelerate ionospheric ions and increase the escape rate. Ionospheric plasma has a composition that reflects the composition of the planet's atmosphere (e.g., abundant O^+ for the Earth and H^+ for the outer planets).

The interaction of magnetospheric plasma with any natural satellites or ring particles that are embedded in the magnetosphere must also be considered; sources of this type can generate significant quantities of plasma. The outermost layers of a satellite's atmosphere can be ionized by interacting with the magnetospheric plasma. Energetic particle sputtering of the satellite surface or atmosphere produces ions of lower energy than the incident energy through a direct interaction but also can create an extensive cloud of neutral atoms that are subsequently ionized, possibly far from the satellite. The distributed sources of water-product ions (totaling ~2 kg s^{-1}) in the magnetosphere of Saturn suggest that energetic particle sputtering of the rings and icy satellites is an important process. Although the sputtering process, which removes at most a few microns of surface ice per thousand years, is probably insignificant in geological terms, sputtering has important consequences for the optical properties of the satellite or ring surfaces.

Table 3 summarizes the basic characteristics of plasmas measured in the magnetospheres of the planets that have detectable magnetic fields. The composition of the ionic species indicates the primary sources of magnetospheric plasma: satellites in the cases of Jupiter, Saturn, and Neptune; the planet's ionosphere in the case of Uranus. In the magnetospheres where plasma motions are driven by the solar wind, solar wind plasma enters the magnetosphere, becoming the primary source of plasma in the case of Mercury's small magnetosphere and a secondary plasma source at Uranus and Neptune. At Earth, both the ionosphere and the solar wind are important sources. Earth's moon remains well beyond the region in which sputtering or other plasma effects are important. In the magnetospheres where plasma flows are dominated by the planet's rotation (Jupiter, Saturn, and within a few R_E of Earth's surface), the plasma is

TABLE 3 **Plasma Characteristics of Planetary Magnetospheres**

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
Maximum density (cm^{-3})	~1	1–4000	>3000	~100	3	2
Composition	H^+	O^+, H^+	O^{n+}, S^{n+}	O^+, $H_2O^+H^+$	H^+	N^+, H^+
Dominant source	Solar wind	Ionosphere[a]	Io	Rings, Enceladus, Tethys, Dione	Atmosphere	Triton
Strength (ions/s)	?	2×10^{26}	$>10^{28}$	$>10^{26}$	10^{25}	10^{25}
(kg/s)		5	700	2	0.02	0.2
Lifetime	Minutes	Days[a] Hours[b]	10–100 days	30 days–years	1–30 days	~1 day
Plasma motion	Solar wind driven	Rotation[a] Solar wind[b]	Rotation	Rotation	Solar wind + rotation	Rotation (+ solar wind?)

[a] Inside plasmasphere.
[b] Outside plasmasphere.

confined by the planet's strong magnetic field for many days so that densities can become relatively high.

4.2 Energy

Plasmas of different origins can have very different characteristic temperatures. Ionospheric plasma has a temperature on the order of ~10,000 K or ~1 eV, much higher than temperature of the neutral atmosphere from which it formed (<1000 K) but much lower than the ~1 keV temperature characteristic of plasmas of solar wind origin, which are heated as they cross the bow shock and subsequently thermalized. Plasmas from satellite sources extract their energy from the planet's rotation through a complicated process. When the neutrals are ionized, they experience a Lorentz force as a result of their motion relative to the surrounding plasma; this force accelerates both ions and electrons, which then begin to gyrate about the magnetic field at a speed equal to the magnitude of the neutral's initial velocity relative to the flowing plasma. At the same time, the new ion is accelerated so that its bulk motion (the motion of the instantaneous center of its circular orbit) moves at the speed of the incident plasma, close to corotation with the planet near the large moons of Jupiter and Saturn. Because the electric field pushes them in opposite directions, the new ion and its electron separate after ionization. Hence a radial current develops as the ions are "picked up" by the magnetic field and the associated Lorentz force at the equator acts to accelerate the newly ionized particles to the local flow speed. The radial current in the near equatorial region is linked by field-aligned currents to the planet's ionosphere where the Lorentz force is in the direction opposite to the planet's rotation (i.e., in a direction that slows (insignificantly) the ionospheric rotation speed). Thus, the planet's angular momentum is tapped electrodynamically by the newly ionized plasma.

In the hot, tenuous plasmas of planetary magnetospheres, collisions between particles are very rare. By contrast, in the cold, dense plasmas of a planet's ionosphere, collisions allow ionospheric plasmas to conduct currents and cause ionization, charge exchange, and recombination. Cold, dense, collision-dominated plasmas are expected to be in thermal equilibrium, but such equilibrium was not originally expected for the hot, tenuous collisionless plasmas of the magnetosphere. Surprisingly, even hot, tenuous plasmas in space are generally found not far from equilibrium (i.e., their particle distribution functions are observed to be approximately **Maxwellian**, though the ion and electron populations often have different temperatures). This fact is remarkable because the source mechanisms tend to produce particles whose initial energies fall in a very narrow range. Although time scales for equilibration by means of **Coulomb collisions** are usually much longer than transport time scales, a distribution close to equilibrium is achieved by interaction with waves in the plasma. Space plasmas support many different types of plasma waves, and these waves grow when free energy is present in the form of non-Maxwellian energy distributions, unstable spatial distributions, or anisotropic velocity–space distributions of newly created ions. Interactions between plasma waves and particle populations not only bring the bulk of the plasma toward thermal equilibrium but also accelerate or scatter suprathermal particles.

Plasma detectors mounted on spacecraft can provide detailed information about the particles' velocity distribution, from which bulk parameters such as density, temperature, and flow velocity are derived, but plasma properties are determined only in the vicinity of the spacecraft. Data from planetary magnetospheres other than Earth's are limited in duration and spatial coverage so there are considerable gaps in our knowledge of the changing properties of the many different plasmas in the solar system. Some of the most interesting space plasmas, however, can be remotely monitored by observing emissions of electromagnetic radiation. Dense plasmas, such as Jupiter's plasma torus, comet tails, Venus's ionosphere, and the solar corona, can radiate collisionally excited line emissions at optical or UV wavelengths. Radiative processes, particularly at UV wavelengths, can be significant sinks of plasma energy. Figure 10 shows an image of optical emission from the plasma that forms a ring deep within Jupiter's magnetosphere near the orbit of its moon, Io (see Section 6). Observations of these emissions give compelling evidence of the temporal and spatial variability of the Io plasma torus. Similarly, when magnetospheric particles bombard the planets' polar atmospheres, various auroral emissions are generated from radio to x-ray wavelengths and these emissions can also be used for remote monitoring of the system. [*See* ATMOSPHERES OF THE GIANT PLANETS.] Thus, our knowledge of space plasmas is based on combining the remote sensing of plasma phenomena with available spacecraft measurements that provide "ground truth" details of the particles' velocity distribution and of the local electric and magnetic fields that interact with the plasma.

4.3 Energetic Particles

Significant populations of particles at keV–MeV energies, well above the energy of the thermal population, are found in all magnetospheres. The energetic particles are largely trapped in long-lived radiation belts (summarized in Table 4) by the strong planetary magnetic field. Where do these energetic particles come from? Since the interplanetary medium contains energetic particles of solar and galactic origins an obvious possibility is that these energetic particles are "captured" from the external medium. In most cases, the observed high fluxes are hard to explain without identifying additional internal sources. Compositional evidence supports the view that some fraction of the thermal plasma is accelerated to high energies, either by tapping the rotational

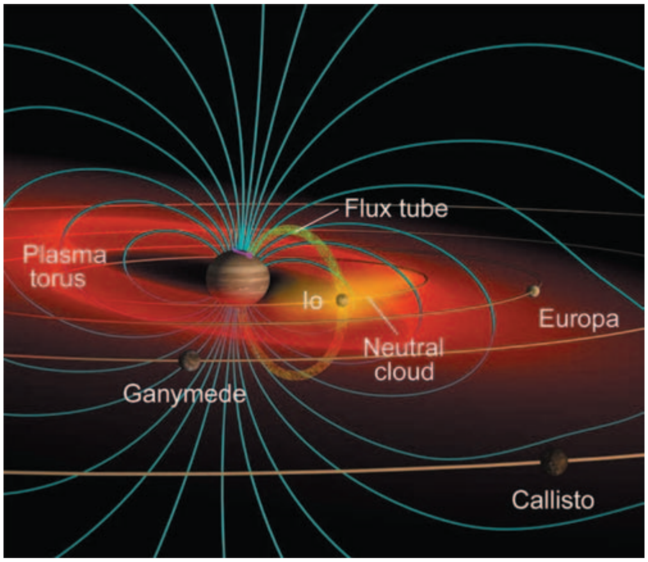


FIGURE 10 The ionization of an extended atmosphere of neutral atoms (yellow) around Jupiter's moon Io is a strong source of plasma, which extends around Jupiter in a plasma torus. Electrical currents generated in the interaction of Io with the surrounding plasma couple the moon to Jupiter's atmosphere where they stimulate auroral emissions. The main ring of auroral emissions is associated with currents generated as the plasma from the Io torus spreads out into the vast, rotating magnetosphere of Jupiter. Credit: John Spencer.

energy of the planet, in the cases of Jupiter and Saturn, or by acceleration in the distorted and dynamic magnetic field in the magnetotails of Earth, Uranus, and Neptune. In a nonuniform magnetic field and particularly in a rapidly rotating magnetosphere, the ions and electrons drift at different speeds around the planet, producing an azimuthal electric current. If the energy density of the energetic particle populations is comparable to the magnetic field energy density, the azimuthal current produces magnetic perturbations that significantly modify the planetary magnetic field. Table 4 shows that this occurs at Jupiter and Saturn, where the high particle pressures inflate and stretch out the magnetic field and generate a strong azimuthal current in the magnetodisc. Even though Uranus and Neptune have significant radiation belts, the energy density of particles remains small compared with the magnetic field and the azimuthal current is very weak. In Earth's magnetosphere, the azimuthal current, referred to as the **ring current,** is extremely variable, as discussed in Section 5. Relating the magnetic field produced by the azimuthal current to the kinetic energy of the trapped particle population (scaled to the dipole magnetic energy external to the planet), we find that even though the total energy content of magnetospheres varies by many orders of magnitude and the sources are very different, the net particle energy builds up to only 1/1000 of the magnetic field energy in each magnetosphere. Earth, Jupiter, and Saturn all have energetic particle populations close to this limit. The energy in the radiation belts of Uranus and

TABLE 4 **Energetic Particle Characteristics in Planetary Magnetospheres**

	Earth	Jupiter	Saturn	Uranus	Neptune
Phase space density[a]	20,000	200,000	60,000	800	800
Plasma beta[b]	<1	>1	>1	~0.1	~0.2
Ring current, ΔB (nT)[c]	10–200	200	10	<1	<0.1
Auroral power (W)	10^{10}	10^{14}	10^{11}	10^{11}	$<10^{8}$

[a] The phase space density of energetic particles (in this case 100 MeV/Gauss ions) is measured in units of (cm^{2}s sr MeV)$^{-1}$ and is listed near its maximum value.

[b] The ratio of the thermal energy density to magnetic energy density of a plasma, $\beta = nkT/(B^2\mu_0)$. These values are typical for the body of the magnetosphere. Higher values are often found in the tail plasma sheet and, in the case of the Earth, at times of enhanced ring current.

[c] The magnetic field produced at the surface of the planet due to the ring current of energetic particles in the planet's magnetosphere.

Neptune is much below this limit, perhaps because it is harder to trap particles in nondipolar magnetic fields.

Where do these energetic particles go? Most appear to diffuse inward toward the planet. Loss processes for energetic particles in the inner magnetospheres are ring and satellite absorption, charge exchange with neutral clouds, and scattering by waves so that the particles stream into the upper atmospheres of the planets where they can excite auroral emission and deposit large amounts of energy, at times exceeding the local energy input from the sun.

The presence of high fluxes of energetic ions and electrons of the radiation belts must be taken into account in designing and operating spacecraft. At Earth, relativistic electron fluxes build to extremely high levels during magnetically active times referred to as storm times. High fluxes of relativistic electrons affect sensitive electronic systems and have caused anomalies in the operation of spacecraft. The problem arises intermittently at Earth but is always present at Jupiter. Proposed missions to Jupiter's moon Europa must be designed with attention to the fact that the energetic particle radiation near Europa's orbit is punishingly intense.

5. Dynamics

Magnetospheres are ever-changing systems. Changes in the solar wind, in plasma source rates, and in energetic cosmic ray fluxes can couple energy, momentum, and additional particle mass into the magnetosphere and thus drive magnetospheric dynamics. Sometimes the magnetospheric response is direct and immediate. For example, an increase of the solar wind dynamic pressure compresses the magnetosphere. Both the energy and the pressure of field and particles then increase even if no particles have entered the system. Sometimes the change in both field and plasma properties is gradual, similar to a spring being slowly stretched. Sometimes, as for a spring stretched beyond its breaking point, the magnetosphere responds in a very nonlinear manner, with both field and plasma experiencing large-scale, abrupt changes. These changes can be identified readily in records of magnetometers (a magnetometer is an instrument that measures the magnitude and direction of the magnetic field), in scattering of radio waves by the ionosphere or emissions of such waves from the ionosphere, and in the magnetic field configuration, plasma conditions and flows, and energetic particle fluxes measured by a spacecraft moving through the magnetosphere itself.

Auroral activity is the most dramatic signature of magnetospheric dynamics and it is observed on distant planets as well as on Earth. Records from ancient days include accounts of the terrestrial aurora (the lights flickering in the night sky that inspired fear and awe), but the oldest scientific records of magnetospheric dynamics are the measurements of fluctuating magnetic fields at the surface of the Earth. Consequently, the term **geomagnetic activity** is used to refer to magnetospheric dynamics of all sorts. Fluctuating magnetic signatures with time scales from seconds to days are typical. For example, periodic fluctuations at frequencies between ~1 mHz and ~1 Hz are called magnetic pulsations. In addition, impulsive decreases in the horizontal north–south component of the surface magnetic field (referred to as the H-component) with time scales of tens of minutes occur intermittently at latitudes between 65° and 75° often several times a day. The field returns to its previous value typically in a few hours. These events are referred to as **substorms.** A signature of a substorm at a ~70° latitude magnetic observatory is shown in Fig. 11. The H-component decreases by hundreds to 1000 nT (the Earth's surface field is 31,000 nT near the equator). Weaker signatures can be identified at lower and higher latitudes. Associated with the magnetic signatures and the current systems that produce them are other manifestations of magnetospheric activity including particle precipitation and auroral

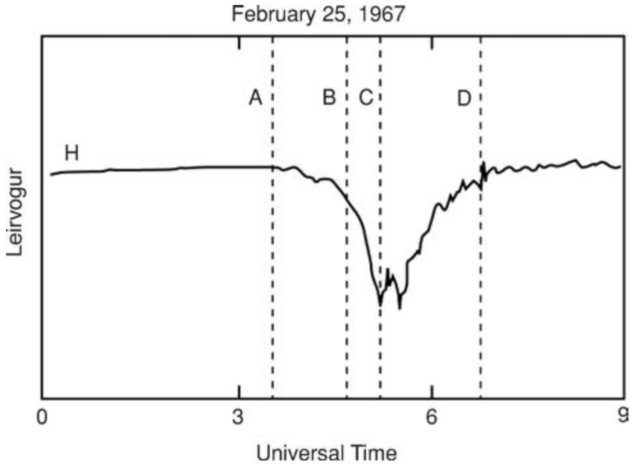


FIGURE 11 The variation of the H component of the surface magnetic field of the Earth at an auroral zone station at 70° magnetic latitude plotted versus universal time in hours during a 9-hour interval that includes a substorm. Perturbations in H typically range from 50 to 200 nT during geomagnetic storms. Vertical lines mark: A, The beginning of the growth phase during which the magnetosphere extracts energy from the solar wind, and the electrical currents across the magnetotail grow stronger. B, The start of the substorm expansion phase during which currents from the magnetosphere are diverted into the auroral zone ionosphere and act to release part of the energy stored during the growth phase. Simultaneously, plasma is ejected down the tail to return to the solar wind. C, The end of the substorm onset phase and the beginning of the recovery phase during which the magnetosphere returns to a stable configuration. D, The end of the recovery phase.

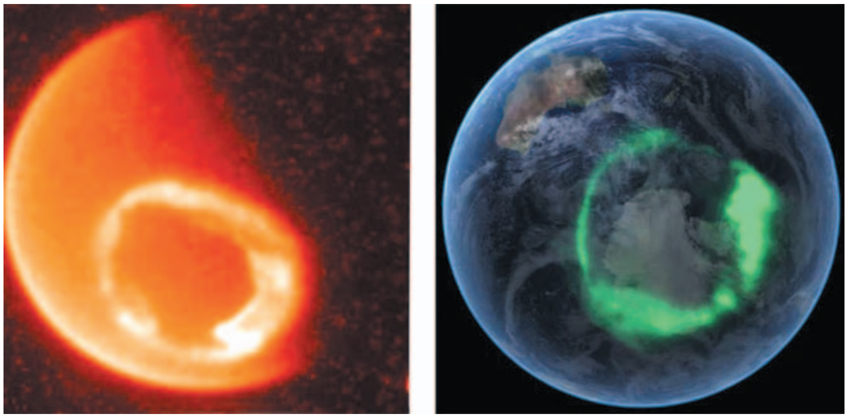


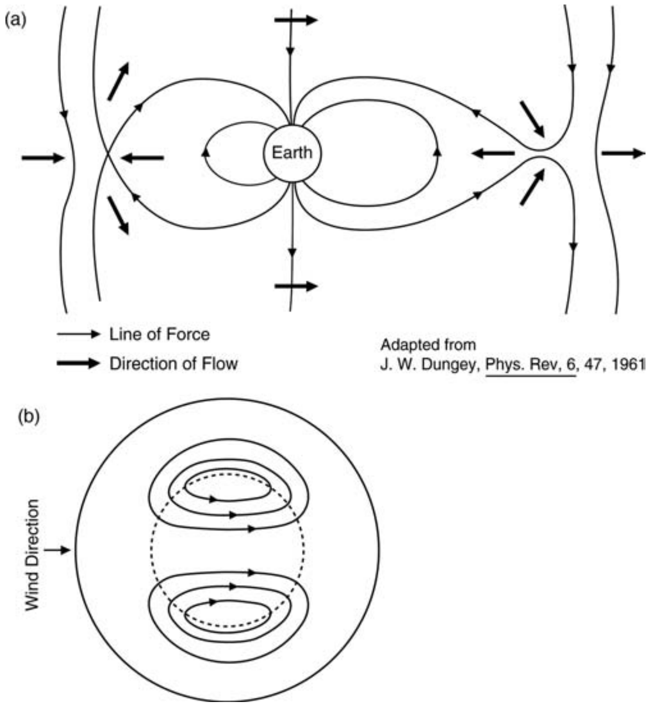
FIGURE 12 (Left) The image shows Earth's aurora observed with the Far Ultraviolet Imaging System on the *IMAGE* spacecraft during a major geomagnetic storm that occurred on July 15, 2000. The picture was obtained when the *IMAGE* spacecraft was at a distance of 7.9 Earth radii, and was looking down onto the northern polar region. The Sun is to the left. The auroral emissions are from molecular nitrogen that is excited by precipitating electrons. Photo credit: S. Mende and H. Frey, University of California, Berkeley. (Right) An ultraviolet image of aurora overlaid on a NASA visible image of the Earth. The aurora occurred during a strong geomagnetic storm on September 11, 2005. Photo credit: NASA. http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=17165.

activation in the polar region and changes within the magnetosphere previously noted.

The auroral activity associated with a substorm can be monitored from above by imagers on spacecraft. The dramatic intensification of the brightness of the aurora as well as its changing spatial extent can thereby be accurately determined. Figure 12 shows an image of the aurora taken by the Far Ultraviolet Imaging System on the IMAGE spacecraft on July 15, 2000. Note that the intense brightness is localized in a high latitude band surrounding the polar regions. This region of auroral activity is referred to as the auroral oval. Only during very intense substorms does the auroral region move far enough equatorward to be visible over most of the United States.

The intensity of substorms and other geomagnetic activity is governed to some extent by the speed of the solar wind but of critical importance is the orientation of the magnetic field embedded in the solar wind incident on a magnetized planet. The fundamental role of the magnetic field in the solar wind may seem puzzling. It is the orientation of the interplanetary magnetic field that is critical, and at Earth it is normally tilted southward when substorm activity is observed. The issue is subtle. Magnetized plasma flowing through space is frozen to the magnetic field. The high conductivity of the plasma prevents the magnetic field from diffusing through the plasma, and, in turn, the plasma particles are bound to the magnetic field by a "$\mathbf{v} \times \mathbf{B}$" Lorentz force that causes the particles to spiral around a field line. How, then, can a plasma ion or electron move from a solar wind magnetic field line to a magnetospheric field line?

The coupling arises through a process called reconnection, which occurs when plasmas bound on flux tubes with oppositely directed fields approach each other sufficiently closely. The weak net field at the interface may be too small to keep the plasma bound on its original flux tube and the field connectivity can change. Newly linked field lines will be bent at the reconnection location. The curvature force at the bend accelerates plasma away from the reconnection site. At the day side magnetopause, for example, solar wind magnetic flux tubes and magnetospheric flux tubes can reconnect in a way that extracts energy from the solar wind and allows solar wind plasma to penetrate the magnetopause. A diagram first drawn in a French café by J. W. Dungey in 1961 (and reproduced frequently thereafter) provides the framework for understanding the role of magnetic reconnection in magnetospheric dynamics (Fig. 13). Shown in the diagram on the top are southward-oriented solar wind field lines approaching the day side magnetopause. Just at the nose of the magnetosphere, the northern ends of the solar wind field lines break their connection with the southern ends, linking instead with magnetospheric fields. Accelerated flows develop near the reconnection site. The reconnected field lines are dragged tailward by their ends within the solar wind, thus forming the tail lobes. When the magnetic field of the solar wind points strongly northward



Adapted from J. W. Dungey, Phys. Rev, 6, 47, 1961

FIGURE 13 Adapted from the schematic view of reconnection sketched by J. W. Dungey in 1961. (a) A noon–midnight cut through the magnetosphere showing from left to right, in addition to two dipole-like field lines (rooted at two ends in the Earth): a solar wind field line with plasma flowing earthward; a newly reconnected pair of field lines, one of solar wind origin and one dipole-like field line, with plasma flowing toward the reconnection point from two sides near the midplane and accelerated both north and south away from the reconnection point; two reconnected field lines with one end in the solar wind and one end in the Earth flowing over the polar caps; two field lines about to reconnect in the magnetotail carried by plasma flow toward the midplane of the diagram; and a newly reconnected field line moving further away from the Earth in the solar wind. (b) A view down on the northern polar cap showing flow lines moving from day to night near the center, above the auroral zone, and returning to the day side at latitudes below the auroral zone.

at Jupiter or Saturn, reconnection is also thought to occur at the low latitude day side magnetopause, but the full process has not yet been documented by observations, although there is some evidence that auroral displays intensify at Jupiter as at Earth when magnetopause reconnection is occurring. At Earth, if the reconnection is persistent, disturbances intensify. Energetic particle fluxes increase and move to low latitudes and the ring current (see Section 4.3) intensifies.

If day side reconnection occurs at Earth, the solar wind transports magnetic flux from the day side to the night side. The path of the foot of the flux tube crosses the center of the polar cap, starting at the polar edge of the day side auroral zone and moving to the polar edge of the night side auroral zone as shown schematically in Fig. 13a. Ultimately that flux must return, and the process is also shown, both in the magnetotail where reconnection is shown closing a flux tube that had earlier been opened on the day side and in the polar cap (Fig. 13b) where the path of the foot of the flux tube appears at latitudes below the auroral zone, carrying the flux back to the day side. In the early stage of a substorm (between A and B in Fig. 11), the rate at which magnetic flux is transported to the night side is greater than the rate at which it is returned to the day side. This builds up stress in the tail, reducing the size of the region within the tail where the magnetic configuration is dipole-like and compressing the plasma in the plasma sheet (see Fig. 1). Only after reconnection starts on the night side (at B in Fig.11) does flux begin to return to the day side. Complex magnetic structures form in the tail as plasma jets both earthward and tailward from the reconnection site. In some cases, the magnetic field appears to enclose a bubble of tailward-moving plasma called a **plasmoid**. At other times, the magnetic field appears to twist around the earthward- or tailward-moving plasma in a flux rope (see Fig. 5). Even on the day side magnetopause, twisted field configurations seem to develop as a consequence of reconnection, and, because these structures are carrying flux tailward, they are called **flux transfer events.**

The diversity of the processes associated with geomagnetic activity, their complexity and the limited data on which studies of the immense volume of the magnetosphere must be based have constrained our ability to understand details of substorm dynamics. However, both new research tools and anticipated practical applications of improved understanding have accelerated progress toward the objective of being able to predict the behavior of the magnetosphere during a substorm. The new tools available in this century include a fleet of spacecraft in orbit around and near the Earth (*ACE*, *Wind*, *Polar*, *Geotail*, *Cluster*, *Double Star*, and several associated spacecraft) that make coordinated measurements of the solar wind and of different regions within the magnetosphere, better instruments that make high time resolution measurements of particles and fields, spacecraft imagers covering a broad spectral range, ground radar systems, and networks of magnetometers. The anticipated applications relate to the concept of forecasting **space weather** much as we forecast weather on the ground. An ability to anticipate an imminent storm and take precautions to protect spacecraft in orbit, astronauts on space stations, and electrical systems on the surface (which can experience power surges during big storms) has been adopted as an important goal by the space science community, and improvements in our understanding of the dynamics of the magnetosphere will ultimately translate into a successful forecasting capability.

Dynamical changes long studied at Earth are also expected in the magnetospheres of the other planets. In passes through Mercury's magnetosphere, the *Mariner* spacecraft observed substorms that lasted for minutes. These will be investigated by the *Messenger* spacecraft in the next decade. Substorms or related processes should also occur at the outer planets, but the time scale for global changes in a system is expected to increase as its size increases. For a magnetosphere as large as Jupiter's, the equivalent of a substorm is not likely to occur more often than every few days or longer, as contrasted with several each day for Earth. Until December 1995 when *Galileo* began to orbit Jupiter, no spacecraft had remained within a planetary magnetosphere long enough to monitor its dynamical changes. Data from Galileo's 8-year orbital reconnaissance of Jupiter's equatorial magnetosphere demonstrate unambiguously that this magnetosphere like that of Earth experiences intermittent injections of energetic particles and, in the magnetotail, unstable flows correlated with magnetic perturbations of the sort that characterize terrestrial substorms. Yet the source of the disturbances is not clear. The large energy density associated with the rotating plasma suggests that centrifugally driven instabilities must themselves contribute to producing these dynamic events. Plasma loaded into the magnetosphere near Io may ultimately be flung out down the magnetotail, and this process may be intermittent, possibly governed both by the strength of internal plasma sources and by the magnitude of the solar wind dynamic pressure that determines the location of the magnetopause. Various models have been developed to describe the pattern of plasma flow in the magnetotail as heavily loaded magnetic flux tubes dump plasma on the night side, but it remains ambiguous what aspects of the jovian dynamics are internally driven and what aspects are controlled by the solar wind.

Whether or not the solar wind plays a role in the dynamics of the jovian magnetosphere, it is clear that a considerable amount of solar wind plasma enters Jupiter's magnetosphere. One way to evaluate the relative importance of the solar wind and Io as plasma sources is to estimate the rate at which plasma enters the magnetosphere when day side reconnection is active and compare that estimate with the few × 10^{28} ions /s whose source is Io. If the solar wind near Jupiter flows at 400 km/s with a density of 0.5 particles/cm^3, it carries $\sim 10^{31}$ particles/s onto the circular cross section of a magnetosphere with $>50\ R_J$ radius. If reconnection is approximately as efficient as it is at Earth, where a 10% efficiency is often suggested, and if a significant fraction of the solar wind ions on reconnected flux tubes enter the magnetosphere, the solar wind source could be important, and, as at Earth, the solar wind may contribute to the variability of Jupiter's magnetosphere. *Galileo* data are still being analyzed in the expectation that answers to the question of how magnetospheric dynamics are controlled are contained in the archives of the mission.

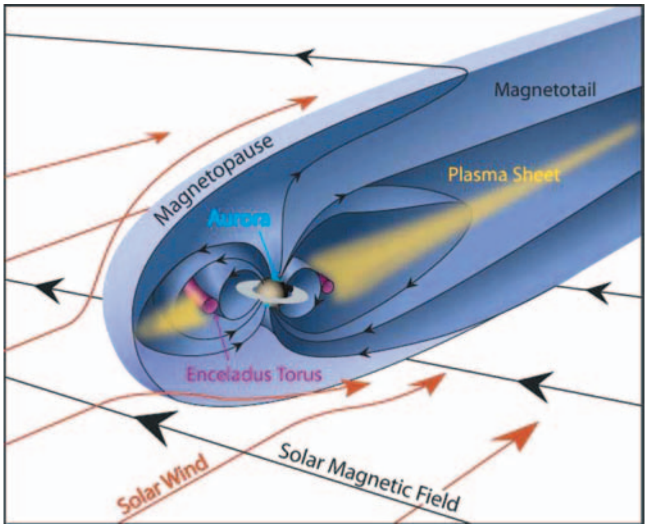


FIGURE 14 Saturn's magnetosphere shown in three dimensions. Water vapor from Enceladus' plumes is dissociated and ionized to form a torus of plasma that diffuses out into an equatorial plasma sheet. Credit: Steve Bartlett

Cassini arrived at Saturn in mid 2004. Earlier passes through the magnetosphere (*Voyager 1* and *2* and *Pioneer 10*) were too rapid to provide insight into the dynamics of Saturn's magnetosphere or even to identify clearly the dominant sources of plasma (Fig. 14). Periodic features had been found in the magnetometer data, and the intensity of radio emissions in the kilometric wavelength band varied at roughly the planetary rotation period, but the source of the periodic variations was unclear because Saturn's magnetic moment is closely aligned with its spin axis, and there is no evident longitudinal asymmetry. The *Cassini* data confirm the strong periodic variation of field and particle properties. There is evidence that the period changes slowly, which makes it likely that the source of periodicity is not linked to the deep interior of the planet, but there is not yet consensus on the source of the periodicity.

The energetic particle detector on *Cassini* is capable of "taking pictures" of particle fluxes over large regions of the magnetosphere. The technique relies on the fact that if an energetic ion exchanges charge with a slow-moving neutral, a fast-moving neutral particle results. The energetic particle detector then acts like a telescope, collecting energetic neutrals instead of light and measuring their intensity as a function of the look direction. The images show that periodic intensifications and substorm-like acceleration are present at Saturn.

It is still uncertain just how particle transport operates at Saturn and how the effects of rotation compare in importance with convective processes imposed by interaction with the solar wind. It seems quite possible that with a major source of plasma localized close to the planet (see discussion of the plume of Enceladus in Section 6), Saturn's magnetospheric dynamics will turn out to resemble those of Jupiter more closely than those of Earth. Observations scheduled in the coming years will surely bear on this speculation.

6. Interactions with Moons

Embedded deeply within the magnetosphere of Jupiter, the four Galilean moons (Io, Europa, Ganymede, and Callisto whose properties are summarized in Table 5) are immersed in magnetospheric plasma that corotates with Jupiter (i.e., flows once around Jupiter in each planetary spin period). At Saturn, Titan, shrouded by a dense atmosphere, is also embedded within the flowing plasma of a planetary magnetosphere. [*See* Titan.] In the vicinity of these moons, interaction regions with characteristics of induced or true magnetospheres develop. The scale of each interaction region is linked to the size of the moon and to its electromagnetic properties. Ganymede, Callisto, and Titan are similar in size to Mercury; Io and Europa are closer in size to Earth's Moon. Io is itself the principal source of the plasma in which it is embedded. Approximately 1 ton(s) of ions is introduced into Jupiter's magnetosphere by the source at Io, thus creating the Io plasma torus alluded to in Section 4. The other moons, particularly Europa and Titan, are weaker plasma sources.

The magnetospheric plasma sweeps by the moons in the direction of their orbital motion because the Keplerian orbital speeds are slow compared with the speed of local plasma flow. Plasma interaction regions develop around the moons, with details depending on the properties of the moon. Only Ganymede, which has a significant internal magnetic moment, produces a true magnetosphere.

The interaction regions at the moons differ in form from the model planetary magnetosphere illustrated in Fig. 1. An important difference is that no bow shock forms upstream of the moon. This difference can be understood by recognizing that the speed of plasma flow relative to the moons is smaller than either the sound speed or the Alfvén speed, so that instead of experiencing a sudden decrease of flow speed across a shock surface, the plasma flow can be gradually deflected by distributed pressure perturbations upstream of a moon. The ratio of the thermal pressure to the magnetic pressure is typically small in the surrounding plasma, and this minimizes the changes of field geometry associated with the interaction. Except for Ganymede, the magnitude of the magnetic field changes only very near the moon. Near each of the unmagnetized moons the magnetic field rotates because the plasma tied to the external field slows near the body but continues to flow at its unperturbed speed both above and below. The effect is that expected if the field lines are "plucked" by the moon. The regions containing rotated field lines are referred to as Alfvén wings. Within the Alfvén wings, the field connects to the moon and its surrounding ionosphere. Plasma on these flux tubes is greatly affected by the presence of the moon. Energetic particles may be depleted as a result of direct absorption, but low-energy plasma densities may increase locally because the moon's atmosphere serves as a plasma source. In many cases, strong plasma waves, a signature of anisotropic or non-Maxwellian particle distributions, are observed near the moons.

In the immediate vicinity of Io, both the magnetic field and the plasma properties are substantially different from those in the surrounding torus because Io is a prodigious source of new ions. The currents associated with the ionization process greatly affect the plasma properties in Io's immediate vicinity. When large perturbations were first observed near Io it seemed possible that they were signatures of an internal magnetic field, but multiple passes established that the signatures near Io can be interpreted purely in terms of currents flowing in the plasma.

Near Titan, the presence of an extremely dense atmosphere and ionosphere also results in a particularly strong

TABLE 5 **Properties of Major Moons of Jupiter and Saturn**

Moon	Orbit Distance (R_P)	Rotation Period (Earth days)[a]	Radius (km)	Radius of Core (moon radii)[b]	Mean Density (kg/m^3)	Surface *B* at Dipole Equator (nT)	Approx. Average B_{ext} (nT)[c]
Io	5.9	1.77	1821	0.25–0.5	3550	$\leq$200	−1900
Europa	9.4	3.55	1570		2940	0 or small	−420
Ganymede	15	7.15	2631	0.25–0.5	1936	750	−90
Callisto	26	16.7	2400		1850	0 or small	−30
Titan	20	15.9	2575		1900	0 or small	−5.1

[a] Jupiter's rotation period is 9 hours 55 minutes, so corotating plasma moves faster than any of the moons.

[b] Core densities can be assumed in the range from 5150 to 8000 kg/m^3. This corresponds to maximum and minimum core radii, respectively.

[c] The magnetic field of Jupiter at the orbits of the moons oscillates in both magnitude and direction at Jupiter's rotation period of 9 hours 55 minutes. The average field over a planetary rotation period is southward oriented (i.e., antiparallel to Jupiter's axis of rotation). Neither the orbits nor the spin axes of the moons are significantly inclined to Jupiter's equatorial plane, so we use averages around the moon's orbit from the model of Khurana and Kivelson (1997).

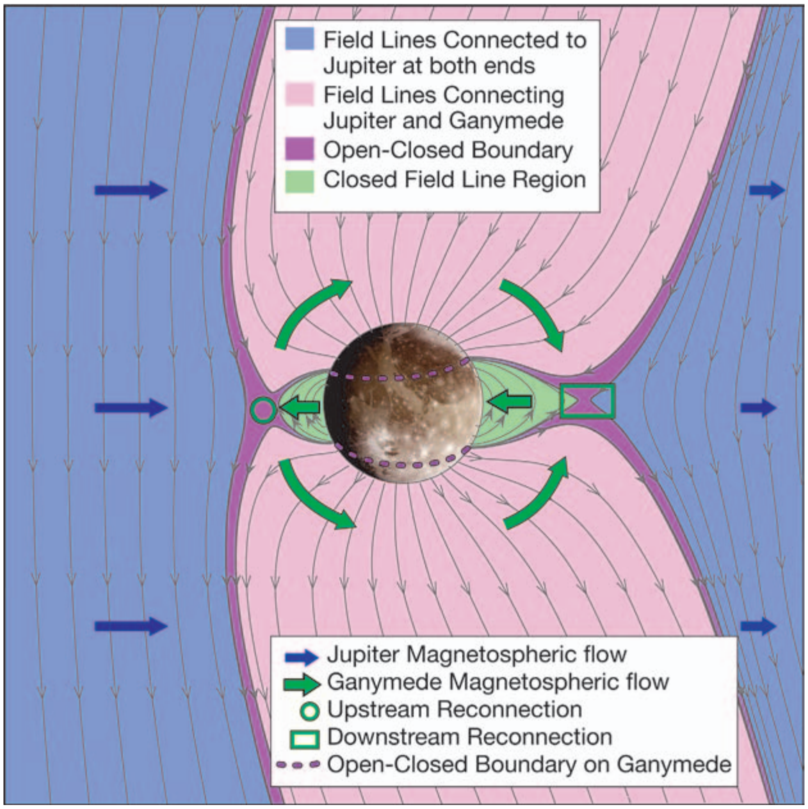


FIGURE 15 A schematic view of Ganymede's magnetosphere embedded in Jupiter's magnetospheric field in a plane that is normal to the direction of corotation flow. The thick purple line that bounds the region in which field lines link to Ganymede is the equivalent of the magnetopause and the polar cusp in a planetary magnetosphere. Credit: Steve Bartlett.

interaction whose effects on the field and the flow were observed initially by *Voyager 1*; the region will be explored thoroughly by the *Cassini* orbiter. Saturn's magnetospheric field drapes around the moon's ionosphere much as the solar wind field drapes to produce the magnetosphere of Venus, a body that like Titan has an exceptionally dense atmosphere.

Saturn's tiny moon, Enceladus, orbiting deep within the magnetosphere at 4 R_S, has proved to be a significant source of magnetospheric heavy ions. Alerted by anomalous draping of the magnetic field to the possibility that high-density ionized matter was present above the south pole of the moon, the trajectory of *Cassini* was modified to enable imaging instruments to survey the region. A plume of vapor, largely water, was observed to rise far above the surface. This geyser is a major source of Saturn's magnetospheric plasma and thus plays a role much like that of Io at Jupiter.

One of the great surprises of the *Galileo* mission was the discovery that Ganymede's internal magnetic field not only exists but is strong enough to stand off the flowing plasma of Jupiter's magnetosphere and to carve out a bubble-like magnetospheric cavity around the moon. A schematic of the cross section of the magnetosphere in the plane of the background field and the upstream flow is illustrated in Fig. 15. Near Ganymede, both the magnetic field and the plasma properties depart dramatically from their values in the surroundings. A true magnetosphere forms with a distinct magnetopause separating the flowing jovian plasma from the relatively stagnant plasma tied to the moon. Within the magnetosphere, there are two types of field lines. Those from low latitudes have both ends linked to Ganymede and are called closed field lines. Little plasma from sources external to the magnetosphere is present on those field lines. The field lines in the polar regions are linked at one end to Jupiter. The latter are the equivalent of field lines linked to the solar wind in Earth's magnetosphere and are referred to as open field lines. On the open field lines, the external plasma and energetic charged particles have direct access to the interior of the magnetosphere. The particle distributions measured in the polar regions are extremely anisotropic because the moon absorbs a large fraction of the flux directed toward its surface. Where the energetic particles hit the surface, they change the reflectance of the ice, so the regions of open field lines can be identified in images of Ganymede's surface and compared with the regions inferred from magnetic field models. The two approaches are in good agreement. As expected, the angular distribution of the reflected particles has also been found to be modified by Ganymede's internal dipole field.

Ganymede's dipole moment is roughly antiparallel to Jupiter's, implying that the field direction reverses across the near equatorial magnetopause. This means that magnetic reconnection is favored. Should future missions allow a systematic study of this system, it will be of interest to learn whether with steady upstream conditions reconnection occurs as a steady process or whether it occurs with some periodic or aperiodic modulation.

7. Conclusions

We have described interactions between flowing plasmas and diverse bodies of the solar system. The interaction regions all manifest some of the properties of magnetospheres. Among magnetospheres of magnetized planets, one can distinguish (a) the large, symmetric, and rotation-dominated magnetospheres of Jupiter and Saturn; (b) the small magnetosphere of Mercury where the only source of plasma is the solar wind that drives rapid circulation of material through the magnetosphere [*see* MERCURY]; and (c) the moderate-sized and highly asymmetric magnetospheres of Uranus and Neptune, whose constantly changing configuration does not allow substantial densities of plasma to build up. The Earth's magnetosphere is an interesting hybrid of the first two types, with a dense corotating plasmasphere close to the planet and tenuous plasma, circulated by the solar wind driven convection, in the outer region. All of these magnetospheres set up bow shocks in the solar wind. The nature of the interaction of the solar wind with nonmagnetized objects depends on the presence of an atmosphere that becomes electrically conducting when ionized. Venus and Mars have tightly bound atmospheres so that the region of interaction with the solar wind is close to the planet on the sunward-facing side, with the interplanetary magnetic field draped back behind the planet to form a magnetotail. Bow shocks form in front of both these magnetospheres. The regions on the surface of Mars where strong magnetization is present produce mini-magnetospheres whose properties are being explored. Comets cause the solar wind field to drape much as at Venus and Mars; they produce clouds extended over millions of kilometers. The interaction of the solar wind with the cometary neutrals weakens or eliminates a bow shock. Small bodies like asteroids disturb the solar wind without setting up shocks. Within the magnetospheres of Saturn and Jupiter, the large moons interact with the subsonic magnetospheric flow, producing unique signatures of interaction with fields that resist draping. No shocks have been observed in these cases.

The complex role of plasmas trapped in the magnetosphere of a planetary body must be understood as we attempt to improve our knowledge of the planet's internal structure, and this means that the study of magnetospheres links closely to the study of intrinsic properties of planetary systems. Although our understanding of the dynamo process is still rather limited, the presence of a planetary magnetic field has become a useful indicator of properties of a planet's interior. As dynamo theory advances, extensive data on the magnetic field may provide a powerful tool from which to learn about the interiors of planets and large satellites. For example, physical and chemical models of interiors need to explain why Ganymede has a magnetic field while its neighbor of similar size, Callisto, does not and why Uranus and Neptune's magnetic fields are highly nondipolar and tilted while Jupiter's and Saturn's fields are nearly dipolar and aligned.

Continued exploration of the plasma and fields in the vicinity of planets and moons is needed to reveal features of the interactions that we do not yet understand. We do not know how effective reconnection is in the presence of the strong planetary fields in which the large moons of Jupiter are embedded. We have not learned all we need to know about moons as sources of new ions in the flow. We need many more passes to define the magnetic fields and plasma distributions of some of the planets and all of the moons because single passes do not provide constraints sufficient to determine more than the lowest order properties of the internal fields. Temporal variability of magnetospheres over a wide range of times scales makes them inherently difficult to measure, especially with a single spacecraft. Spurred by the desire to understand how the solar wind controls geomagnetic activity, space scientists combine data from multiple spacecraft and from ground-based instruments to make simultaneous measurements of different aspects of the Earth's magnetosphere or turn to multiple spacecraft missions like *Cluster* and *Themis* and the much anticipated Magnetospheric Multiscale Mission. As it orbited Jupiter, the *Galileo* spacecraft mapped out different parts of the jovian magnetosphere, monitoring changes and measuring the interactions of magnetospheric plasma with the Galilean satellites. *Cassini* in orbit around Saturn will provide even more complete coverage of the properties of another magnetosphere and its interaction with Titan. The properties of the magnetic and plasma environment of Mars are still being clarified by spacecraft measurements. *Messenger* is en route to Mercury where it will go into orbit with instruments that will characterize the mysterious magnetic field of this planet. And finally, Pluto beckons as the prototype of an important new group of solar system bodies; the dwarf planets. It is sure to interact with the solar wind in an interesting way. As new technologies lead to small, lightweight instruments, we look forward to missions of the new millennium that will determine if Pluto or Charon have magnetic fields and help us understand the complexities of magnetospheres large and small throughout the solar system.

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