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Planetary Magnetospheres and the Interplanetary Medium

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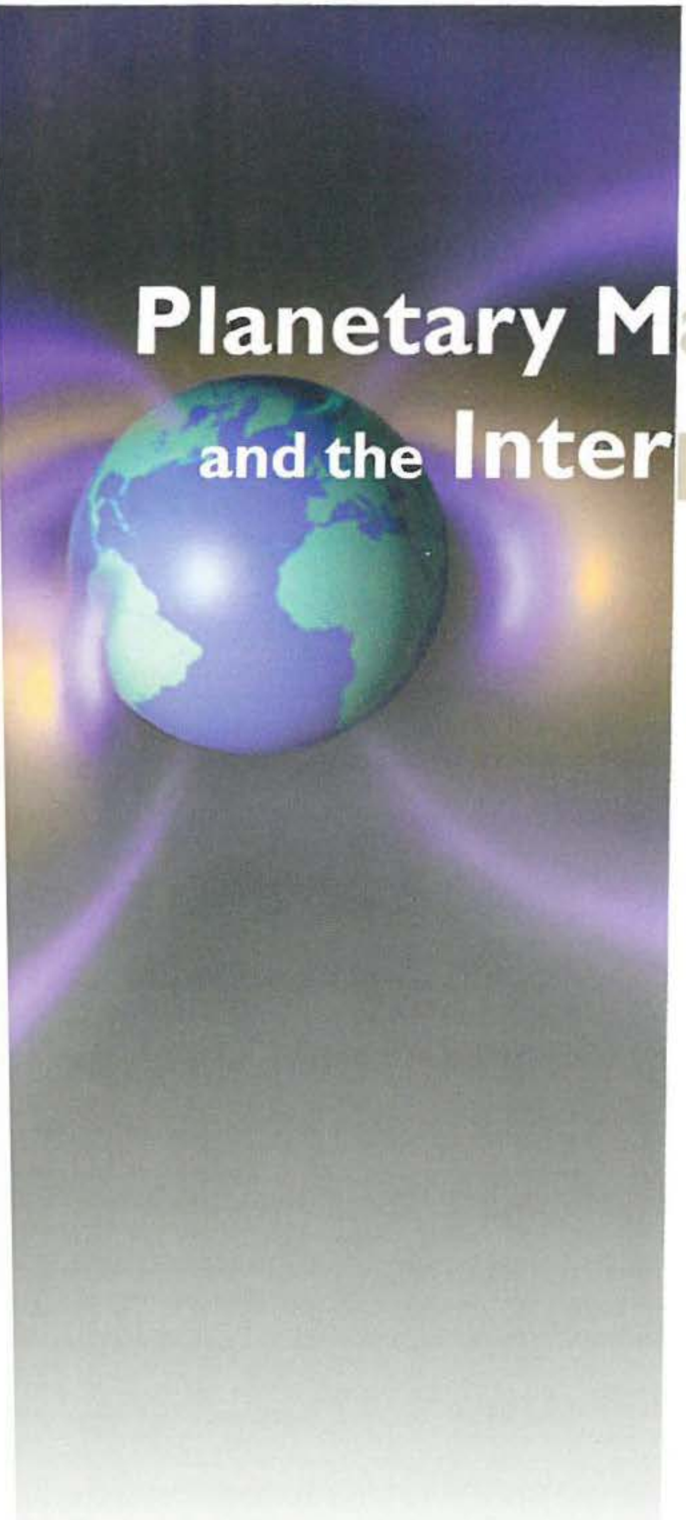


The Van Allen belts, high-energy charged particles trapped in Earth's magnetopshere.

THE CONCEPT OF interplanetary space generally conjures up an image of a vast, tranquil void of complete emptiness. The environment between planets is indeed much nearer to a vacuum than that produced in any laboratory. However, in reality it is stormy with energetic particles and radiation flowing from the Sun. This "space weather" changes constantly in step with the variable and sometimes violent solar activity.

One of the excitements of the Space Age has been our unfolding of the complex story of the interplanetary medium and its interaction with the planets (magnetized or not), comets, and asteroids. Magnetospheres are the most important products of such interactions, but there are also other effects. For example, the direct irradiation of otherwise-unprotected surfaces alters their spectral properties and compositions. Atmospheres can be heated, ionized, and eroded by the impinging interplanetary medium. In some cases, magnetic fields shield surfaces from energetic particles very effectively, conceivably accommodating — or frustrating — the development of life.

Virtually all of this activity goes unseen at visible wavelengths. It is no coincidence that human eyes have evolved to be most sensitive over the narrow wavelength range at which the Sun's intensity peaks. However, "sunlight" includes a wide spectrum of wavelengths, all of which contribute to the *interplanetary medium*. There are far fewer solar ultraviolet and X-ray photons, but their shorter wavelengths make them more energetic than visible-light photons. Consequently, they create more pronounced effects on upper atmospheres and exposed surfaces. Our Sun is also a tremendous source of radio energy, and it frequently gives off tremendous bursts of X-rays that last from minutes to hours.

THE SOLAR WIND

One of the most engaging detective stories of modern science has been recognition of the existence and importance of solar "corpuscular radiation," that is, gaseous material shed by the Sun, distinct from light and other forms of electromagnetic energy. This outpouring from the Sun's atmosphere, a combination of ionized gas and the entrained solar magnetic field, is now usually termed *solar wind*.

In their great 1940 treatise, *Geomagnetism*, Sydney Chapman and Julius Bartels speculated that fluctuations in Earth's magnetic field (magnetic storms) are caused by solar corpuscular streams. A decade later, the German astronomer Ludwig Biermann showed that the streams were not simply intermittent bursts but were instead a continuous phenomenon (a conclusion he based on observations of comets' bluish gas tails). Over the past half century, instrumented spacecraft have confirmed some, but not all, of these early inferences concerning solar corpuscular streams and have provided a wealth of detailed knowledge about them.

The solar wind consists of a hot *plasma* — an electrically neutral mixture of electrons and ions (principally protons with some heavier atomic nuclei) at roughly 100,000° K. Its source is the Sun's atmosphere, or corona, and it is continuously present in interplanetary space. This gas flows radially outward at a typical speed of 450 km per second to at least 70 AU and probably much farther. The average speed of the flowing gas is remarkably independent of its distance from the Sun.

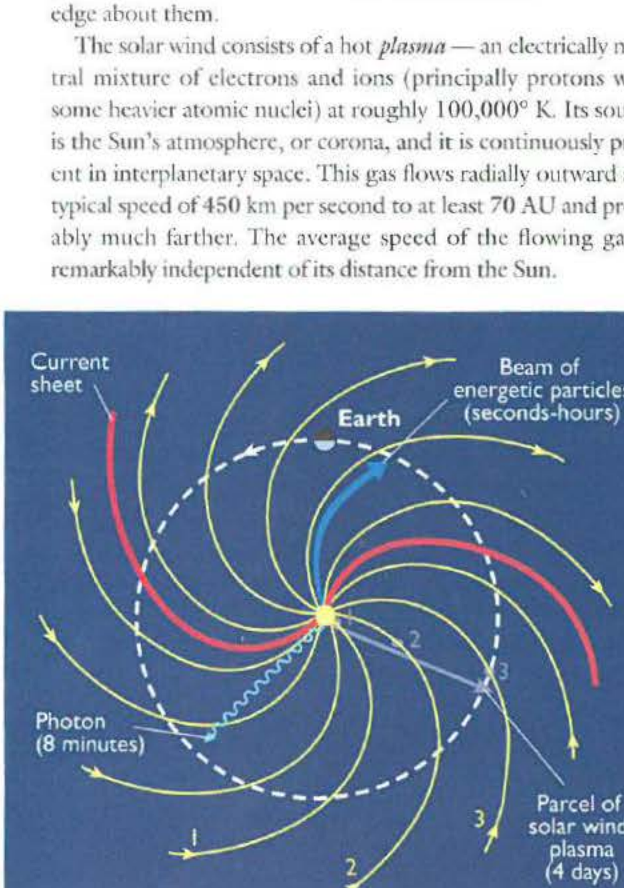


Figure 1. **In the ecliptic plane the radial flow of the solar wind and the rotation of the Sun combine to wind the solar magnetic field into a spiral. A parcel of solar wind plasma (average speed: 450 km per second) takes about 4 days to travel from the Sun to Earth's orbit at 1 AU. The dots and magnetic field lines labeled *1*, *2*, and *3* represent snapshots during this journey. Solar energetic particles travel much more rapidly. Because their trajectories are controlled by the Sun's magnetic field, these particles are scattered by irregularities in the field and thus spread out quickly as they move outward through the heliosphere. The heliospheric *current sheet* separates magnetic fields of opposite polarities.**

Even though the solar corona ejects gas radially outward into interplanetary space, the continuous stream takes on, by virtue of the Sun's rotation, the approximate form of an Archimedean spiral (*Figure 1*). At the orbit of Earth, the spiral makes an angle of about 45° with a radial line from the Sun but becomes nearly perpendicular at the orbit of Saturn (9.5 AU) and beyond.

At Earth's orbit the number density of ions and electrons in interplanetary space is typically five particles per cm^3 under quiet conditions. This population density diminishes as the inverse square of the heliocentric distance, but sporadic order-of-magnitude fluctuations occur in response to varying solar activity. The solar wind's speed is also variable, and a variety of collisionless shock phenomena occur as fast streams overtake slow ones. Outright collisions are rare in this exceedingly dilute interplanetary medium. However, the particles and magnetic field are coupled by electric and magnetic interactions, and these wave-particle phenomena replace collisions as the agent of energy transfer. A wide variety of wave types are carried in the interplanetary medium.

The ionized, electrically conducting gas carries with it an entrained magnetic field that also originates in the solar corona (see Chapter 3). Since the dynamics of the interplanetary medium are dominated by the mass motion of the ionized gas it contains, the magnetic field lines become stretched out approximately parallel to the "wave fronts" of the plasma stream. The magnitude and direction of this field vary markedly from point to point, but it generally parallels the theoretical Archimedean spiral. At 1 AU the magnetic-field strength is typically 5×10^{-9} tesla (or 5 nanotesla), many orders of magnitude less than its levels in the solar chromosphere. Because the field lines assume a tightly wrapped spiral form far from the Sun, the magnetic field's strength does not decrease as quickly as the number density of the plasma does. Instead, it falls off as the inverse of heliocentric distance.

Until recently, direct observations of the solar wind were confined to a thin, pancake-shaped region near the plane of Earth's orbit (the ecliptic), which is approximately the equatorial plane of the Sun. However, studies of the scintillation of stellar radio sources have shown that solar-wind speed increases at locations well above and below the Sun's equator. A marked advance was made by the Ulysses mission, which extended our measurements to latitudes within 10° of the Sun's south and north poles in 1994–1995. At that time, near solar-activity minimum, the solar-wind speed increased abruptly at a latitude of about 20° from its low-latitude value of 400 km per second to 770 km per second (*Figure 2*). Although this finding validated our earlier, less-direct inferences, we do not yet understand why the solar wind is so much faster at high latitudes.

COSMIC RAYS

In 1912 Victor Hess found that a weak but mysterious radiation grew more intense with altitude in Earth's atmosphere. He surmised that it must come from outer space, a conjecture that was soon confirmed. We now realize that this *cosmic radiation* consists of atomic nuclei (principally protons) and a much smaller contribution of electrons. These are termed "primary" particles, and their energies range from tens of millions to many billions of electron volts. Because primary cosmic rays and their progeny are so energetic, they have had an important role in modern high-energy particle physics.

The compositional distribution of cosmic-ray nuclei resembles the relative abundance of nuclei in "universal" matter, as estimated from astrophysical evidence. This is not surprising, since it is widely believed that the more energetic cosmic-ray particles, sometimes called galactic cosmic rays, originate in violent astrophysical events such as supernovas and explosive stellar flares. The Sun also sporadically emits electrons, protons, and heavier ions from its active regions. These *solar energetic particles* range from a few thousand to tens of millions of electron volts in energy, and they travel outward through the interplanetary magnetic field (*Figure 1*). Bursts of such particles last for hours to days, and they pose a serious hazard for human interplanetary travel.

At ground level, instruments detect only cosmic-ray "secondaries," which result when primaries having energies of many billions of electron volts interact with molecules of gas in our atmosphere. As first shown in 1954, the count of secondaries varies by a few percent in step with the 11-year cycle of solar activity, with the intensity peak near the time of solar minimum and vice versa. At balloon altitudes this cyclic variation becomes considerably more pronounced, especially at high latitudes. In near-Earth space, the disparity is even greater, with the maximum cosmic-ray intensity more than twice that at its cyclic minimum. Thus, for lower-energy particles, whose secondaries are unable to reach the ground, the magnitude of the solar-cycle variation is much greater.

The mystery of this cyclic variation in galactic cosmic-ray intensity has intrigued many investigators. Undoubtedly, the effect is attributable to the Sun. The prevailing view is that the magnetic field entrained in the outflowing solar wind acts as a modulating agent. Cosmic rays enter the outer solar system and diffuse inward, but the turbulent magnetic field of the interplanetary medium tends to convect them outward and decelerate them. The process may be likened to a school of fish swimming upstream in a turbulent river. Thus, cosmic rays are relatively rare in the inner solar system — especially the low-energy particles, which are convected and decelerated most easily.

A further mystery, perhaps connected to the issue of solar-cycle modulation of cosmic rays, lies in the variation of cosmic-ray fluxes with solar latitude. At one time we expected that cosmic rays would have relatively free access to the inner solar system along conical spirals of field lines over the Sun's poles. While Ulysses did detect greater numbers of cosmic rays during its high-latitude passes, the increase was much less than expected, particularly at lower energies. An explanation may be rooted in Ulysses's finding that the polar magnetic field is more irregular and less streamlined than expected.

The challenge to space physicists is to determine how well the interplanetary magnetic field repels cosmic-ray particles of a given energy throughout the planetary system and, ultimately, to find the boundary (the *heliopause*) at which the Sun's modulating influence ends. We shall return to the subject of the search for the heliopause later in the chapter.

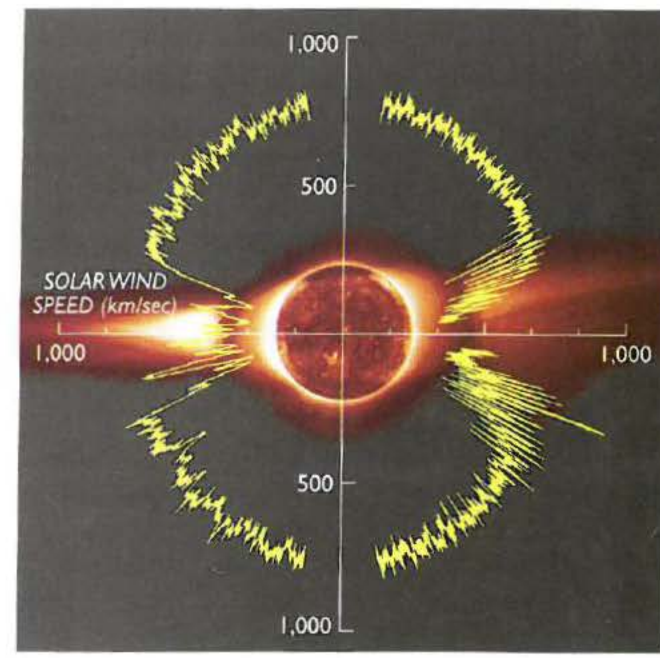


Figure 2. **A composite of an ultraviolet image of the solar disk and white-light images of the solar corona form the backdrop for a radial plot of solar-wind speed versus latitude. These data, obtained by the Ulysses spacecraft between 1991 and 1996, show that the wind escapes into interplanetary space much faster from the Sun's polar regions than from near its equator.**

PLANETARY MAGNETISM

The Sun's powerful magnetic field arises from the turbulent motion of electrically conductive matter, powered by the nuclear fusion going on in its core. The planets do not contain nuclear furnaces, yet somehow they still create and maintain intrinsic magnetic fields. One explanation is that they simply solidified in the presence of the Sun's extended field 4½ billion years ago. The ambient interplanetary field would have become "frozen" into the iron-bearing rocks of Earth and its neighbors. However, the interiors of the largest planets were — and remain — well above the *Curie point*, the temperature below which ferromagnetic materials retain an ambient magnetic field. Smaller bodies have cooled below the Curie point and thus may still have their primordial fields.

Alternatively, global magnetic fields in planetary objects can be generated by an internal *dynamo*. Theories of such a dynamo are complex, and their predictive value is quite limited. Nevertheless, there is general agreement that a dynamo has three basic requirements: (1) a rotating body (2) containing a fluid, electrically conducting region (3) within which convective motion occurs. The necessary rate of rotation is uncertain, but all the planets (except perhaps Venus) and major moons appear to spin sufficiently fast. Likewise, all the planets and many of the larger moons have electrically conducting interior regions. These can take the form of molten rock-iron mixtures (the terrestrial planets and major moons); hydrogen having metallic properties at high pressure and temperature (Jupiter and Saturn); or mixtures of water, ammonia, and methane (Uranus and Neptune).

Another requirement that differentiates the magnetic "haves" and "have nots" is the existence of a thermal gradient across their electrically conducting regions large enough to drive convective motions. In theory, the smaller, rocky objects of the solar system, including the terrestrial planets, should have stably stratified cores that are slowly cooling by conduction. Within rocky bodies having magnetic fields (Earth, Mercury, and possibly Ganymede), dynamo convection is powered by gravitational energy from primordial accretion, the decay of radioactive elements, and heat from chemical transformations. The giant planets, meanwhile, have retained much of their primordial heat, enough to drive vigorous internal convection and power their dynamos. In some cases, ongoing compositional differentiation may be providing an additional source of heat.

Although modern theories of self-sustained dynamos are complex, a plausible scenario was first provided by Eugene Parker in 1955. The fluid inside a planetary body tends to rotate differentially, with the innermost region spinning fastest. If an exterior (roughly north-south) magnetic field penetrates this conducting fluid, it will be wound up into coils of azimuthal or "toroidal" magnetic field. This coiling acts to concentrate and amplify the magnetic field strength in the planet's core. If the conducting fluid is heated and rises, the combination of convection and rotation carries the toroidal loops upward and twists them. The result is a field that reinforces the original (north-south) external field. At that point the process becomes self-sustaining, and the planet's magnetic field is regenerated continuously.

The simplest form of a magnetic field is a *dipole*, analogous to a bar magnet. The simplest general characterization of a planet's intrinsic magnetism is its equivalent dipole *magnetic moment*. The dipole moment divided by the cube of the planet's radius yields the average strength of the field along the magnetic equator (*Table 1*). For example, at Earth's magnetic equator this value is 0.305 gauss or 30,500 nanoteslas (nT). To generate a surface field this strong, thousands of kilometers from its core, Earth must have an impressively large magnetic moment, 7.91×10^{25} gauss cm^3. By comparison, laboratory electromagnets are typically of the order of 100,000 gauss cm^3. We cannot yet explain why Jupiter's magnetic moment is nearly 100 million times that of Mercury, though an obvious factor must be the absolute size of the conducting fluid region.

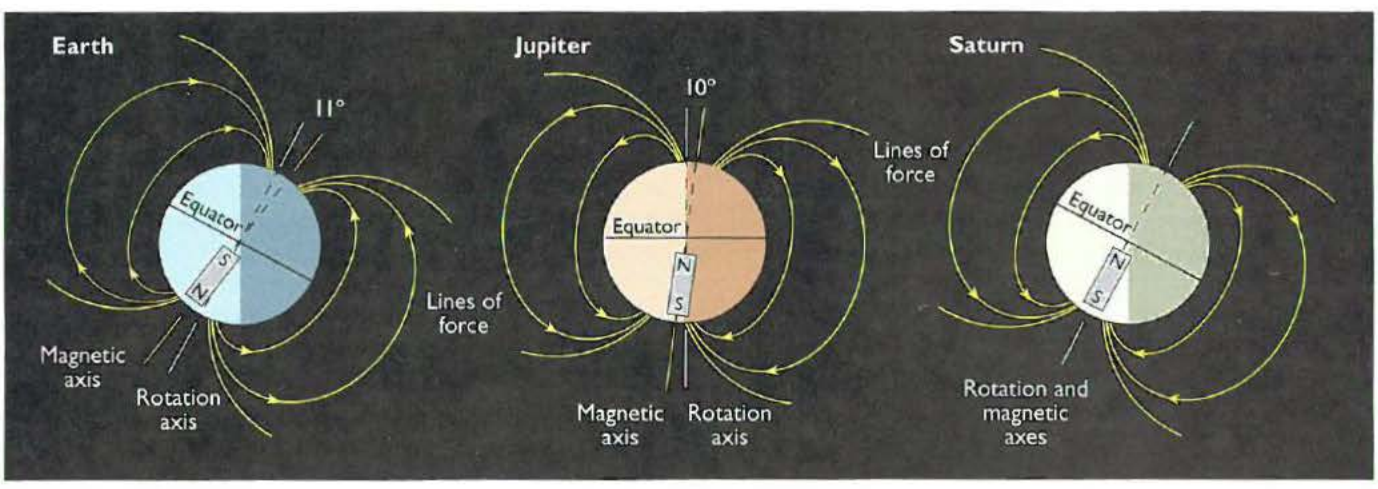
We also do not understand why dipole moments exhibit such a wide range of alignments with respect to the planets' rotation axes (*Figure 3*). Moreover, the dipoles of Mercury and Earth have a polarity opposite that of the other planets. Little significance is placed on this fact, however, since Earth's magnetic field has reversed its polarity many times over geologic time. Of

Characteristics of Planetary Magnetic Fields

	Rotation period (days)	Dipole moment (Earth=1)	Field at equator (gauss)	Polarity same as Earth's?	Angle between axes	Typical magnetopause distance (R_p)	Plasma sources
Mercury	58.65	0.0007	0.003	yes	14°	1.5	W
Venus	243.02(R)	< 0.0004	< 0.00003	—	—	—	W,A
Earth	1.00	1	0.305	yes	10.8°	10	W,A
Mars	1.03	< 0.0002	< 0.0003	—	—	—	—
Jupiter	0.41	20,000	4.28	no	9.6°	80	W,A,S
Saturn	0.44	600	0.22	no	< 1°	20	W,A,S
Uranus	0.72(R)	50	0.23	no	58.6°	20	W,A
Neptune	0.67	25	0.14	no	47°	25	S

Table 1 (above). The solar system's planets exhibit a wide range of magnetic properties. *(R)* indicates retrograde rotation. Earth's magnetic polarity is such that its south magnetic pole lies in the Northern Hemisphere. *Angle between axes* refers to the magnetic and rotational axes. *Typical magnetopause distance* is in the direction of the Sun and given in planetary radii. Under *plasma sources,* the letter *W* is for solar wind, *A* for atmosphere, and *S* for satellites or rings.

Figure 3 (below). No two planetary magnetic fields are alike, as demonstrated by the examples of Earth, Jupiter, and Saturn. Bar magnets represent the planets' dipole fields and magnetic polarities. Throughout a planet's orbit its obliquity and dipole tilt combine to produce a seasonal variation in the angle between the magnetic field axis and the radial distance from the Sun.



greater consequence is the combined effect of the dipole tilt and a planet's obliquity (the inclination of the equator to the orbital plane). This leads to diurnal and seasonal changes between the angle of the solar wind and the dipole moment, sometimes with significant consequences (discussed later).

A planet's external magnetic field can be represented most simply by a point magnetic dipole (a vector with defined magnitude and direction) located at its center. Saturn's field comes closest to the ideal case, in which the rotation and magnetic axes coincide. Point dipoles also provide reasonable approximations for Mercury, Earth, and Jupiter. Maps of the surface fields of Earth and Jupiter show stronger fields at the poles and a magnetic equator (*Figure 4*). By contrast, the magnetic fields of Uranus and Neptune are both offset from these planets' centers and highly inclined with respect to their rotational axes. This creates surface fields that are much stronger in one hemisphere and magnetic equators that weave over the surface. The dynamo motions in their interiors must be very different from those of other planets.

The situation with Mars is less certain. Early spacecraft equipped with magnetometers did not approach very close to the Martian surface. Weak fields were detected, but the planet's dipole moment is no more than 0.0002 that of Earth. Scientists argued for decades over whether the field is due to a dynamo or to currents in the ionosphere. Then, in September 1997, Mars Global Surveyor reached its destination. During its first few orbits the spacecraft came within 120 km of the Martian surface and found regions with surprisingly strong magnetic fields (about 400 nT). However, the field's patchy nature suggests that it is unlikely the result of an active internal dynamo. Instead, the magnetization is probably *remanent*, that is, frozen into expanses of solidifying lava. In time, we should learn whether this lingering field arose from an ancient Martian dynamo, or from ionospheric currents driven by the solar wind (which may have been strong if Mars's early atmosphere was denser than it is now).

TYPES OF MAGNETOSPHERES

Our knowledge of Earth provides the basis for understanding the electromagnetic properties of other planets. However, as our spacecraft emissaries have found, each world exhibits distinctive and unique magnetic properties. A strict definition of a planetary *magnetosphere* is the region surrounding a planet within which its own magnetic field dominates the behavior of electrically charged particles. The term does not imply a spherical shape but is used in a looser sense, as in the phrase "sphere of influence."

The solar wind has a negligible effect on the movements of large bodies. However, it has profound effects in their immediate vicinity, creating an amazing assortment of physical phenomena. Because the solar wind is a plasma, it behaves like an electrically conducting fluid. It is also magnetized; that is, it contains systems of electrical currents that survive from their origin in the solar corona. These two properties, when combined with its bulk flow, are essential to the creation of most magnetospheric phenomena (*Figure 5*).

Upstream of a planetary magnetosphere is a *bow shock*, a standing shock wave that results because the solar wind is supersonic — it moves faster than the waves that are propagating through it. Essentially, the solar wind cannot "sense" the magnetized obstacle in its path soon enough to move smoothly around it. The situation is comparable to the behavior of air around a supersonic aircraft. After passing through the bow shock, the solar wind encounters and flows around the *magnetopause*, the boundary between the solar-wind plasma and the magnetosphere. The magnetic field accompanying the solar wind merges with that of a planet and stretches it out to produce a long, turbulent *magnetotail*, or wake, on the downwind side of the planet. Earth's magnetotail, for example, is several million kilometers long. The *stagnation point*, on the planet's sunward side, is where the solar wind comes closest to the cen-

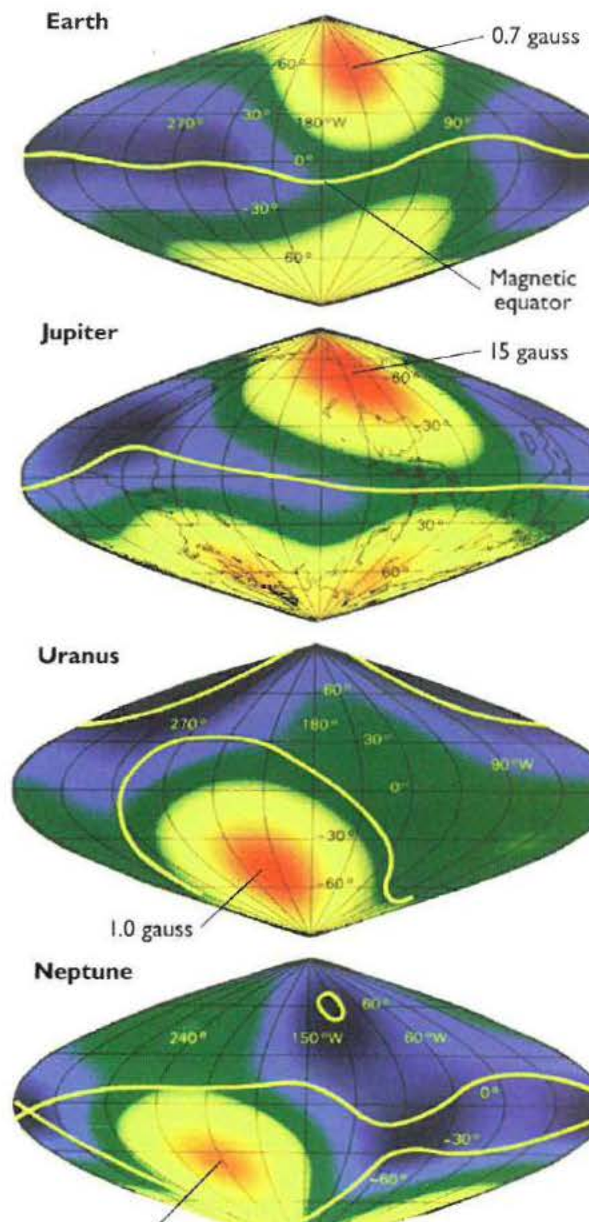


Figure 4. **The magnetic fields on the surface of Earth, Jupiter, Uranus, and Neptune exhibit a wide range of strengths. Note especially how the dipole fields of Uranus and Neptune, which are markedly offset from the planets' centers, create distinctly asymmetric surface fields.**

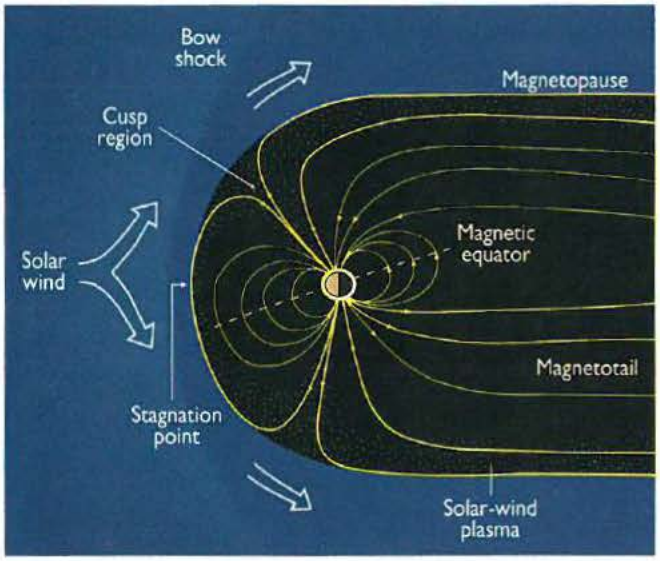


Figure 5. **This portrayal of a generic planetary magnetosphere shows many of the features commonly found around magnetized planets.**

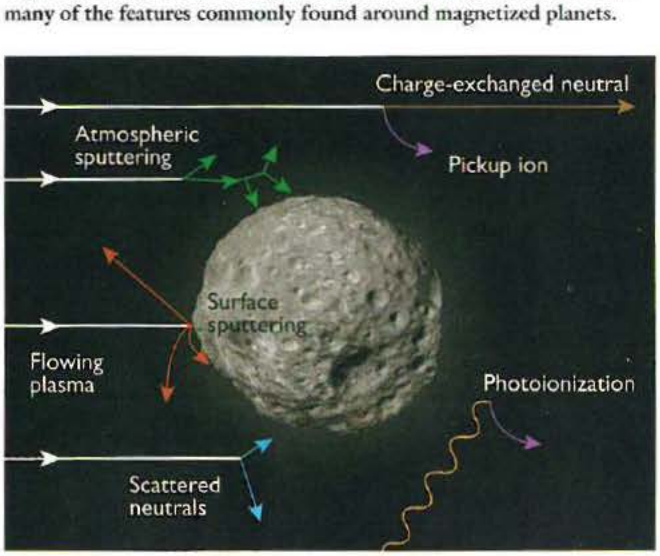


Figure 6. **When plasma (ions and electrons) bombards a surface or atmosphere at high speed, a wide variety of processes can occur.**

ter of the planet. This standoff distance depends upon the ever-changing solar-wind pressure. For Earth, it is usually about 64,000 km away — far above the atmosphere.

The stronger a planet's magnetic field, the larger its magnetosphere. In addition, the weak solar-wind pressures present in the outer solar system allow relatively weak planetary magnetic fields to carve out large cavities. Consequently, the sizes of planetary magnetospheres span a vast range, from the small magnetic bubble surrounding Mercury (which would fit entirely within Earth) to the giant magnetosphere of Jupiter (which is at least a thousand times the volume of the Sun).

The magnetopause is not completely "plasma-tight," however, particularly around the magnetic poles. Consequently, magnetospheres contain considerable amounts of plasma, the main source of which is usually the Sun. Solar-wind plasma has a characteristic composition: protons (H^+), about 4 percent alpha particles (He^{2+}), and traces of heavier nuclei, many of which are highly ionized. Ionospheric plasma has a composition that reflects the composition of the planet's upper atmosphere (for example, O^+ for Earth and H^+ for the outer planets). Natural satellites or ring particles embedded in the magnetosphere can also generate significant quantities of plasma. The residence times of magnetically trapped particles vary widely — from hours to years. Their motion inside a magnetosphere depends on the relative strength of the coupling to the rotating planet compared with that to the solar wind.

As it races outward through the planetary system, the solar wind sometimes encounters a sizable object that lacks an intrinsic magnetic field. If such an object has a surface with a low electrical conductivity, no electrodynamic interaction occurs and the plasma runs directly into the surface. Downstream of the object is wake cavity largely devoid of plasma. This is the type of interaction created by Earth's Moon, and we assume that the same scenario applies to many small, rocky objects of the solar system.

If the nonmagnetic object possesses an atmosphere, the uppermost atoms and molecules are ionized by solar radiation or by impact with the flowing plasma in which they are imbedded (*Figure 6*). This *ionosphere* provides conducting paths for electrical currents to flow into the solar wind, where they create forces that slow and divert the incident flow. The barrier that separates the planetary plasma from the solar wind is referred to as the *ionopause* (analogous to the magnetopause), and the interactions are similar in many ways to those of a true magnetosphere. A bow shock forms upstream if the plasma flow is supersonic, and the solar-wind magnetic field drapes around the planet and forms a magnetotail. This type of magnetosphere is found at Venus and Mars, as well as at comets and satellites that have substantial atmospheres.

HOME TERRITORY: EARTH

Using simple radiation detectors aboard the Explorer 1 and 3 satellites in 1958, James Van Allen and his students discovered that a huge population of energetic charged particles surrounds Earth and remains durably trapped there by our planet's magnetic field. No one had predicted such an effect; indeed, those early instruments were designed to survey cosmic-ray intensities above the atmosphere. The trapped particles form two distinctively different *radiation belts*. (The term "radiation belts" has historical roots; it does not imply radioactivity.) Each population has the shape of a torus and encircles our planet in such a way that its central plane coincides roughly with Earth's magnetic equatorial plane (*Figure 7*).

In 1907, Carl Størmer showed theoretically that an energetic, electrically charged particle can be permanently trapped, or confined, within the magnetic field of a dipole. In any static magnetic field, the force on a moving charged particle is directed at right angles to both the direction of its motion and the magnetic vector. This *Lorentz force* causes the particles to move in spring-shaped paths (*Figure 8*), quickly moving back and forth in magnetic latitude while drifting slowly in longitude. The specific trajectory depends on the particle's momentum and electrical charge, and over time it sweeps out a toroidal volume encircling the dipole.

An important source of radiation-belt particles is neutrons produced when galactic cosmic rays and energetic solar particles

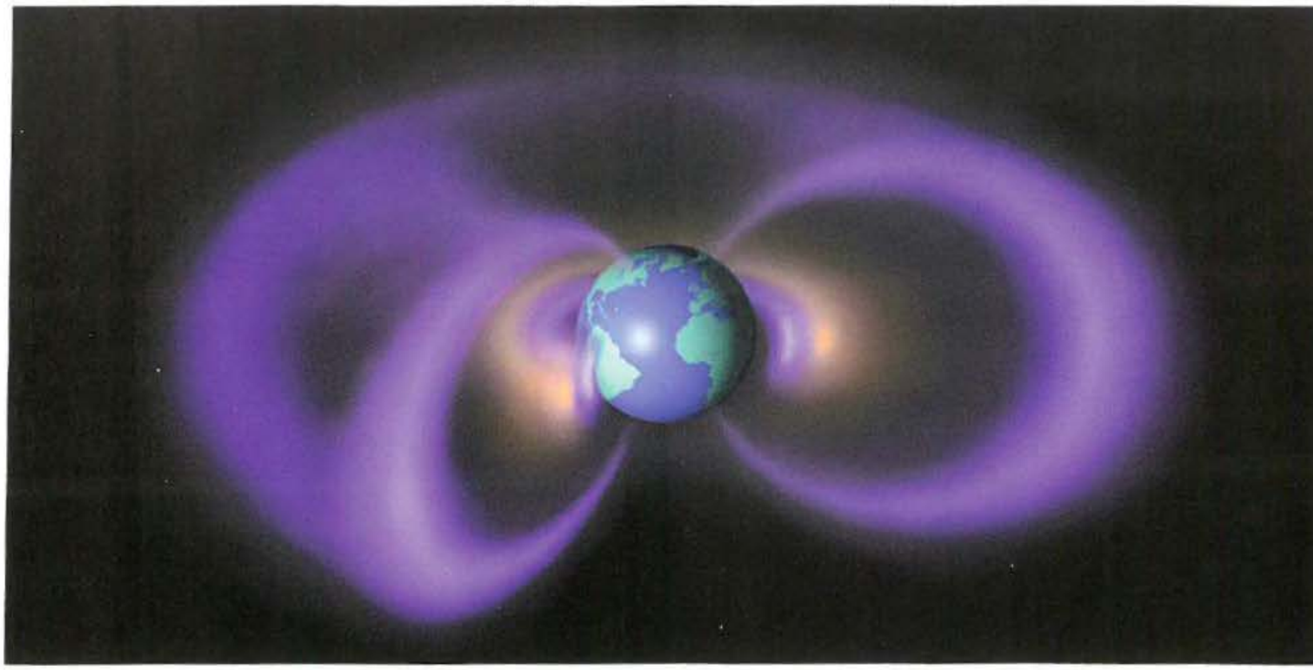


Figure 7 (above). The inner Van Allen belt contains a mixture of trapped charged particles: protons (yellow) with energies greater than 10 million electron volts and electrons (blue) exceeding 500,000 electron volts. The outer belt also contains protons and electrons, most of which have energies under 1.5 million electron volts. Earth's magnetic dipole is offset from its center by about 500 km. Consequently, one side of the inner Van Allen radiation belt comes closer to our planet's surface than the other side does. This region, termed the South Atlantic Anomaly, has affected satellites for four decades.

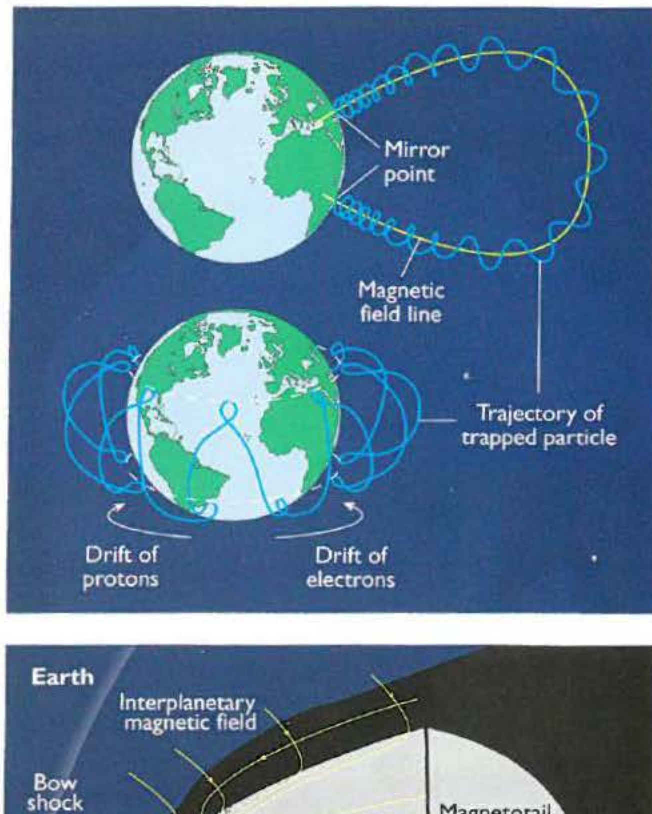


Figure 8 (middle right). Charged particles trapped by a planet's magnetic field follow complex trajectories. They gyrate around the lines of force (upper diagram), bouncing between the regions of stronger magnetic field at the ends of the field lines over intervals of seconds to minutes. They also drift around the planet on time scales of hours. The greater the particle's energy, the less time it takes for each motion.

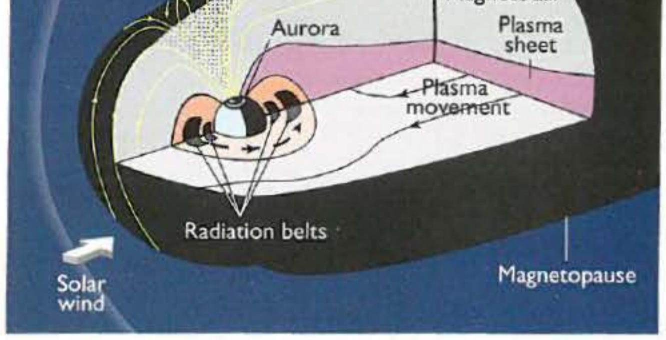


Figure 9 (bottom right). The general shape and principal features of Earth's magnetosphere. Charged particles become trapped in a pair of radiation belts near the planet and in the magnetotail, which extends to the right (well outside this depiction).

bombard Earth's atmosphere. As they fly off into space, a small fraction of these neutrons decay into protons and electrons, which are immediately snared by the magnetic field. The residence times of such particles in trapped orbits depend in part on the ambient field strength. In the strong field present close to Earth, residence times for protons having energies of tens of millions of electron volts are of the order of a decade. So, even though the decay of neutrons provides only a weak source of particles, they remain trapped long enough to accumulate in substantial numbers.

The magnetosphere, especially its outer reaches, is dynamic and constantly changing. "Low-energy" particles (with less than about 10,000 electron volts) have a much greater influence on gross physical phenomena than do their relatively rare "high-energy" counterparts. However, the latter pose hazards

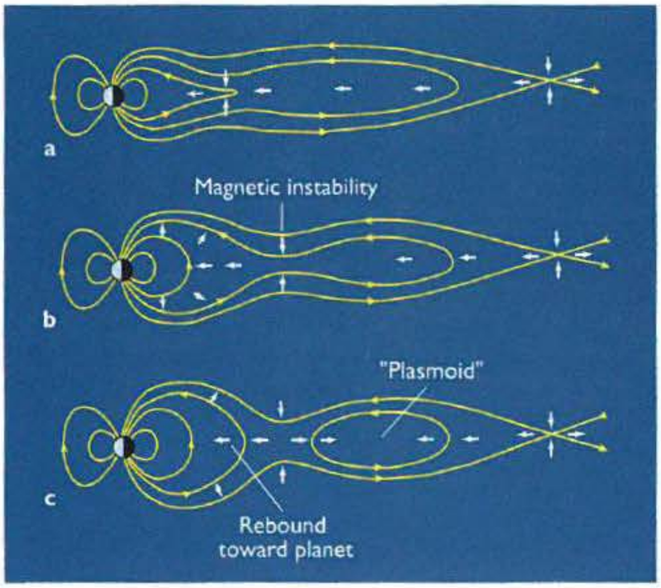


Figure 10. **During a magnetic substorm, changes in solar-wind conditions cause the magnetotail to be pinched off close to Earth. Magnetospheric plasma is accelerated away from this disturbance; a blob of plasma is ejected down the magnetotail, while other particles cascade into Earth's polar regions, often causing auroras.**

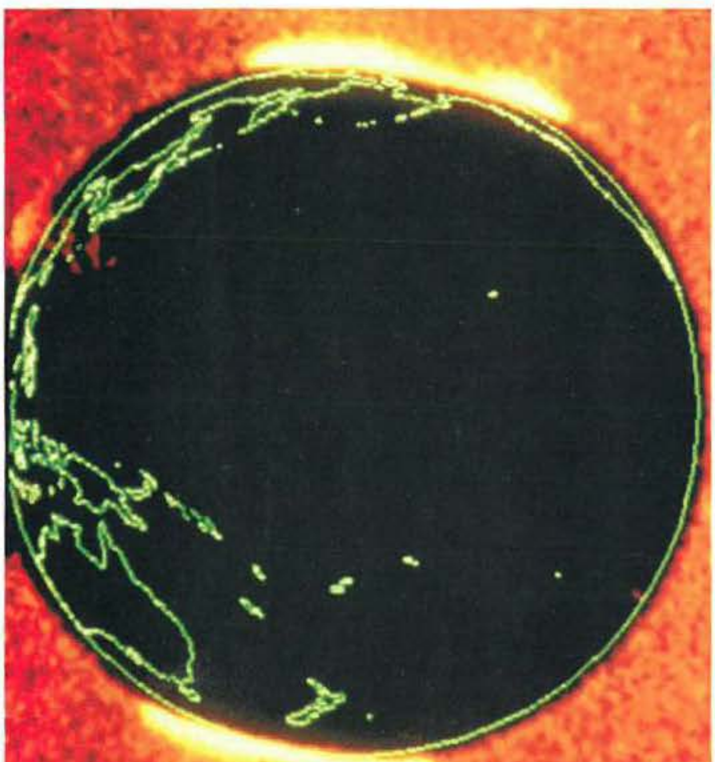


Figure 11. **This extraordinary image from NASA's Dynamics Explorer 1 satellite shows both the aurora borealis ("northern lights") and the aurora australis ("southern lights"). These glowing ovals or rings are about 500 km wide, 4,500 km in diameter, and centered roughly on Earth's magnetic poles. Green lines show major land areas; Australia is at lower left and North America at upper right. Most auroral displays occur at altitudes of 110 to 240 km and appear green (dominated by 5577-angstrom emission from oxygen atoms). Above that, up to 400 km high (rarely to 1,000 km), the aurora has a ruby-red glow from oxygen ions emitting at 6300 and 6364 angstroms.**

to electronic systems and living things, and their distribution places practical limits on the orbits around Earth where human crews and animals are safe from excessive radiation exposure. The most readily accessible region of safe flight lies at altitudes below 400 km. By contrast, the radiation dosage within the equatorial region of the inner radiation belt, at an altitude of about 2,500 km, is especially severe — even electronic instrumentation has a limited useful lifetime there.

Earth's magnetosphere comprises two very different regions, distinguished by the plasma sources and flows in each region (*Figure 9*). Close to Earth, the trapped oxygen ions, protons and electrons derived from the ionosphere corotate with the planet. This *plasmasphere* extends outward to between 25,000 and 40,000 km, and within it lies the terrestrial ring current that causes magnetic storms. The plasmasphere and radiation belts overlap in the inner magnetosphere, where the cold (2,000° K) ionospheric plasma limits the population of energetic radiation-belt particles through complex plasma-wave interactions.

Farther out, the magnetosphere is dominated by its interaction with the solar wind. The plasma in this outer region consists largely of protons and electrons that have leaked in across the magnetopause. Because convection cycles this plasma through the magnetosphere in a matter of hours, it does have a chance to build up to substantial densities. In the magnetotail, on the nightside of Earth's magnetosphere, the solar-wind–driven flow brings the plasma down to the equatorial plane, where it is concentrated in the *plasma sheet*. Changes in the solar wind's condition can disturb the convective flows and trigger an instability in the plasma sheet (*Figure 10*). This disruption, termed a *magnetic substorm*, occurs between 6 and 20 Earth radii down the tail. It causes plasma to flow away from the disturbance up and down the magnetotail, some of which follows magnetic-field lines back toward Earth. At such times the accelerated electrons bombard the upper atmosphere and can generate spectacular auroral displays (*Figure 11*).

Earth's magnetosphere is a natural laboratory for a variety of interactions of plasma with electric and magnetic fields. When the charged-particle population is disturbed or becomes unstable, it generates numerous electrostatic and electromagnetic waves. Taken together, these processes make Earth a strong radio source that radiates roughly 100 million watts into interplanetary space. However, despite its panoply of energetic processes, Earth's magnetic environment is dwarfed by the magnetospheres surrounding Jupiter and Saturn. Their strong planetary magnetic fields allow the magnetospheric plasma to tap the planet's rotational energy and accelerate particles to relativistic energies.

JUPITER: THE MAGNETIC GIANT

As early as 1955, Jupiter was recognized as a source of sporadic bursts of radio noise at a frequency of 22.2 megahertz (decametric wavelengths). These emissions are termed *nonthermal* because they arise from processes other than those associated with heat. Soon thereafter, another type of nonthermal radiation from Jupiter was discovered at much higher frequencies, from 300 to 3,000 megahertz (decimetric wavelengths). Unlike the bursty decametric emission, Jupiter's decimetric radiation has an intensity and spectral form that are nearly constant with time. It comes from a toroidal region whose central plane tilts about 10° to the planet's equatorial plane (*Figure 12*). In 1959, Frank Drake and Hein Hvatum interpreted the decimetric emission as synchrotron radiation emitted by electrons trapped in the Jovian magnetic field and moving at relativistic velocities.

These ground-based observations set Jupiter apart from all other planets and provided an impetus for sending spacecraft to probe its radiation belts directly. Pioneers 10 and 11 encountered Jupiter in late 1973 and 1974, respectively. They confirmed the existence of trapped, relativistic electrons packed several orders of magnitude more densely than in Earth's magnetosphere. Even during their brief encounters, each spacecraft absorbed a thousand times the dosage of high-energy electrons known to cause severe radiation sickness or death in humans. Both Pioneers suffered the failure of several transistor circuits and the darkening of exposed optics.

Jupiter's magnetic moment is tilted 9.6° to its rotational axis, in agreement with the evidence from ground-based radio observations. The general form of the Jovian magnetosphere resembles that of Earth, but its dimensions are at least 1,200 times greater (*Figure 13*). In fact, if we could see this enormous electromagnetic bubble in the nighttime sky, it would appear several times larger than the full Moon. Voyager observations later showed that the magnetotail of Jupiter extends behind it to the orbit of Saturn and beyond — at least 650 million km! These enormous dimensions result from a magnetic moment 20,000 times greater than Earth's and from the fact that the solar-wind pressure at 5.2 AU from the Sun is only about 4 percent of its value here at 1 AU.

Beyond these basic characteristics, the magnetosphere of Jupiter exhibits a rich variety of special and unique features. First, substantial amounts of trapped, energetic plasma exert pressure on the magnetic field, inflating it like an air-filled balloon. Because the field is weakest in its equatorial plane, the outward distention is most prominent there. Second, the magnetic field *corotates* with the planet's interior (once every 9 hours 56 minutes), and the plasma interacting with the field is

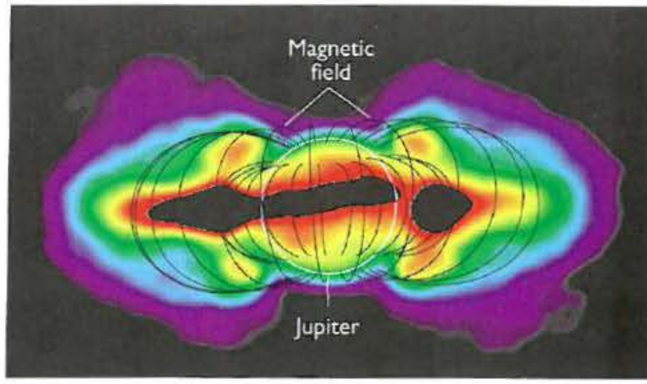


Figure 12. **Jupiter is a strong source of both continuous and sporadic radio energy. This radio map shows the steady, decimetric-wavelength energy emitted by electrons with relativistic energies that are trapped in the Jovian magnetosphere. This type of synchrotron emission is not observed from any other planet but is a common feature of many astrophysical objects, including pulsars.**

forced to circle Jupiter with this period as well. Therefore, centrifugal force pushes the plasma outward.

The combination of these two effects produces a distinctive disk of plasma, or *plasma sheet*, lying roughly in the planet's magnetic equatorial plane (*Figure 13*). As Pioneer 10 and the twin Voyagers flew through Jupiter's magnetosphere they measured particle fluxes that rose and fell as the tilted plasma sheet flopped north and then south over the spacecraft twice per 10-hour rotation period. The exact mechanism that accelerates so many particles to high energies, generating the hot plasma that inflates the magnetosphere, is not known. The source may well be the rapid rotation of Jupiter and the strong coupling of its magnetic field to the trapped magnetospheric plasma.

The first indication that Jupiter's moon Io plays a significant role in the magnetosphere came when E. K. Bigg noticed in 1964 that the bursts of Jovian decametric radio emission are strongly controlled by the moon's orbital longitude. Early clues of the "Io connection" came in the 1970s, when ground-based optical telescopes recorded an extended atmosphere of sodium atoms around Io itself and a cloud of S^+ ions all the way around

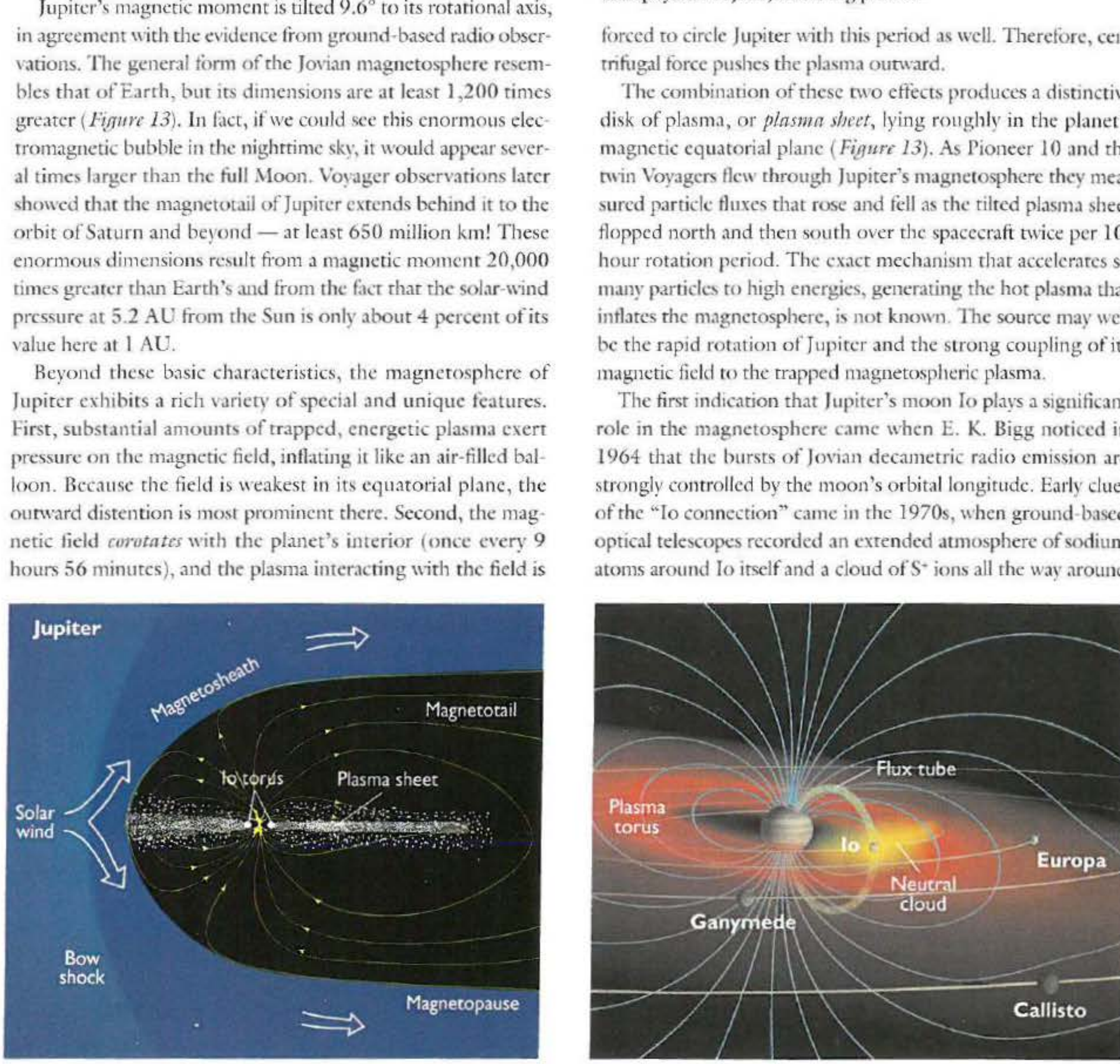


Figure 13. **Jupiter's magnetosphere is an enormous envelope much larger than the Sun. Trapped plasma is concentrated in a disklike *plasma sheet* near the planet's magnetic equator. The inner magnetosphere is portrayed in greater detail in the panel at right. Io is electrodynamically coupled to Jupiter and is the main source of the magnetosphere's plasma.**

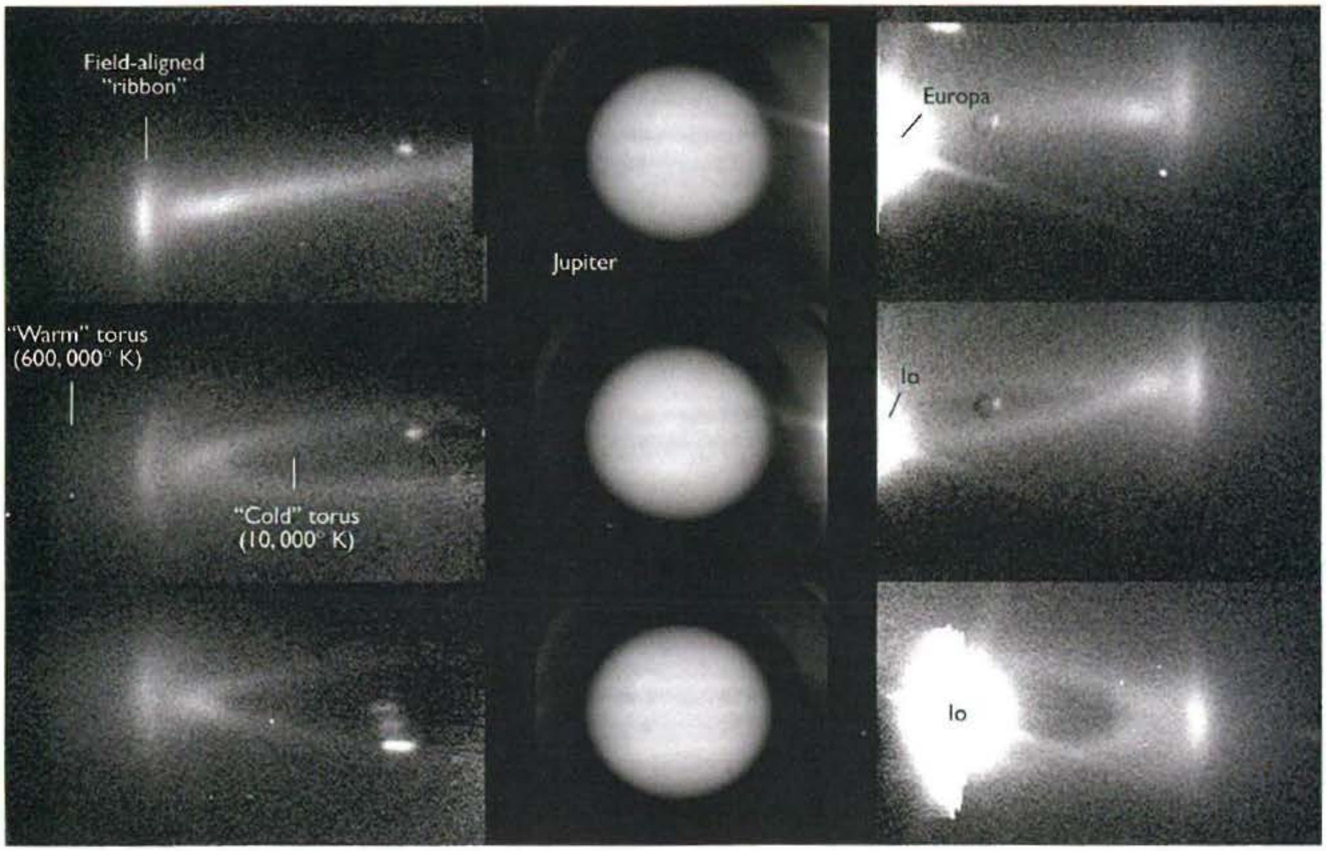


Figure 14. **Molecules from Io's thin atmosphere create a doughnut-shaped ring of matter all along its orbit. Once ionized, these atoms follow the planet's wobbling magnetic field. Astronomers can see this torus thanks to the light emitted by sulfur ions at 6731 angstroms and by neutral sodium atoms at 5890 angstroms. This series shows S^+ emission recorded over 3 hours on 31 January 1991. Each "triptych" is a single image, but the left and right sides have been enhanced to bring out detail. The vertical "ribbons" of enhanced emission at far left and far right roughly coincide with Io's orbit.**

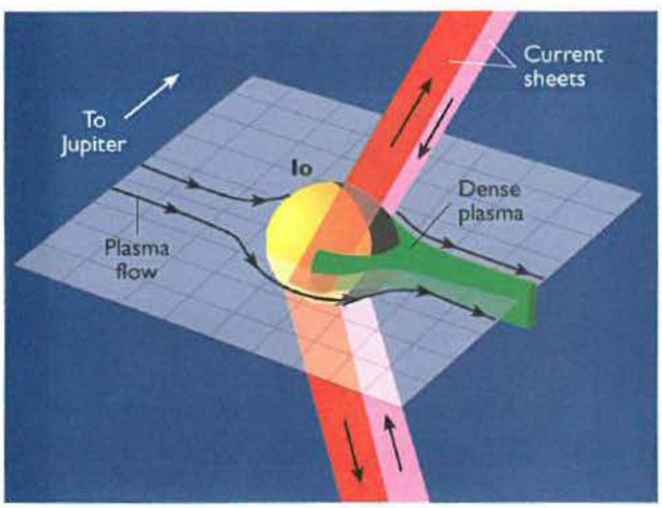


Figure 15. **The plasma interaction at Io with plasma in Jupiter's magnetosphere is complex and not completely understood. However, this innermost Galilean satellite serves as one end of a powerful *current sheet* (sometimes called a "flux tube") of electrons that connect it with the ionosphere of Jupiter. The electrical circuit created along this path is enormous, involving an estimated 400,000 volts and 2 trillion watts of power.**

its orbit (*Figure 14*). As Voyager 1 approached Jupiter in early 1979 it began to detect strong ultraviolet emissions that suggested this toroidal cloud was dense with ions of sulfur and oxygen. Days later the spacecraft flew through Io's plasma torus and found thousands of ions and electrons per cm^3 (comparable to Earth's plasmasphere), temperatures of about 1,000,000° K, and a composition that suggested the dissociation products of sulfur dioxide (SO_2). The source of this gas soon became obvious: volcanic eruptions on Io (see Chapter 17). The ionization of SO_2 products from Io's atmosphere injects roughly a ton of material into the plasma torus every second. It quickly couples to the Jovian magnetic field and accelerates to the 10-hour corotation rate.

Since ground-based and Voyager observations suggested that the magnetospheric interaction with Io is complex, a close flyby of this moon became a major objective for the Galileo mission. Upon reaching Jupiter in December 1995, the spacecraft passed within 900 km of the surface of Io, ahead of the moon in its orbit and thus downstream of the satellite with respect to the rapidly circling magnetospheric plasma. The Galileo instruments detected a dense, cold (low-energy) plasma in the center of the wake and hot plasma on its flanks. The plasma appears to be deflected around Io. The spacecraft's magnetometer also showed a falloff in the magnetic-field strength in the moon's immediate vicinity.

Interpretation of these observations has proved tricky. There is no question that the interaction of the magnetospheric plasma with the atmosphere and ionosphere of Io generates large amounts of new plasma and drives electrical currents through the plasma (and maybe Io itself). Yet controversy rages over whether the observed magnetic signature requires Io to have an internal magnetic field, or whether the observations can be explained by electric currents created by the magnetosphere's interaction with the satellite and its atmosphere. Io most likely has an iron core. However, tidal flexing heats its outer layers, not the core, making a convection-driven dynamo problematic. Some scientists argue that the magnetic signature could be explained entirely by strong currents coursing through Io's ionosphere (and created by interactions with the surrounding magnetosphere). Others counter that the moon's ionosphere is too weakly conducting for these currents to arise.

The ambiguity may soon be resolved. In addition to ongoing detailed modeling of how the moon couples to its electromagnetic surroundings, the last two orbits of the Galileo mission are to include close flybys of Io, one pass upstream and the other over the pole. From these, we expect to get one set of magnetic-field and plasma measurements if Io has an internal magnetic field, and a very different signature if it does not.

Although many questions remain about the interplay between Io and the magnetospheric plasma, it is clear that Io is coupled electrodynamically to Jupiter itself (*Figure 15*). The bursts of decametric radio emission triggered by Io are generated close to Jupiter, presumably at the base of field lines that have been perturbed by Io. Centrifugal forces enable the corotating torus plasma to diffuse slowly outward against the confining forces of Jupiter's magnetic field, and over some tens of days the material fills the giant magnetosphere of Jupiter. However, instead of the ionized gas cooling as it expands, the plasma is somehow accelerated and heated, thereby inflating the middle and outer regions of the magnetosphere. The heating mechanism remains unknown, but the source of energy is generally thought to be the rotation of Jupiter, coupled to the plasma by the magnetic field. In any case, the particles then diffuse inward, gaining additional energy from the magnetic field as they are "recycled" back to the inner magnetosphere.

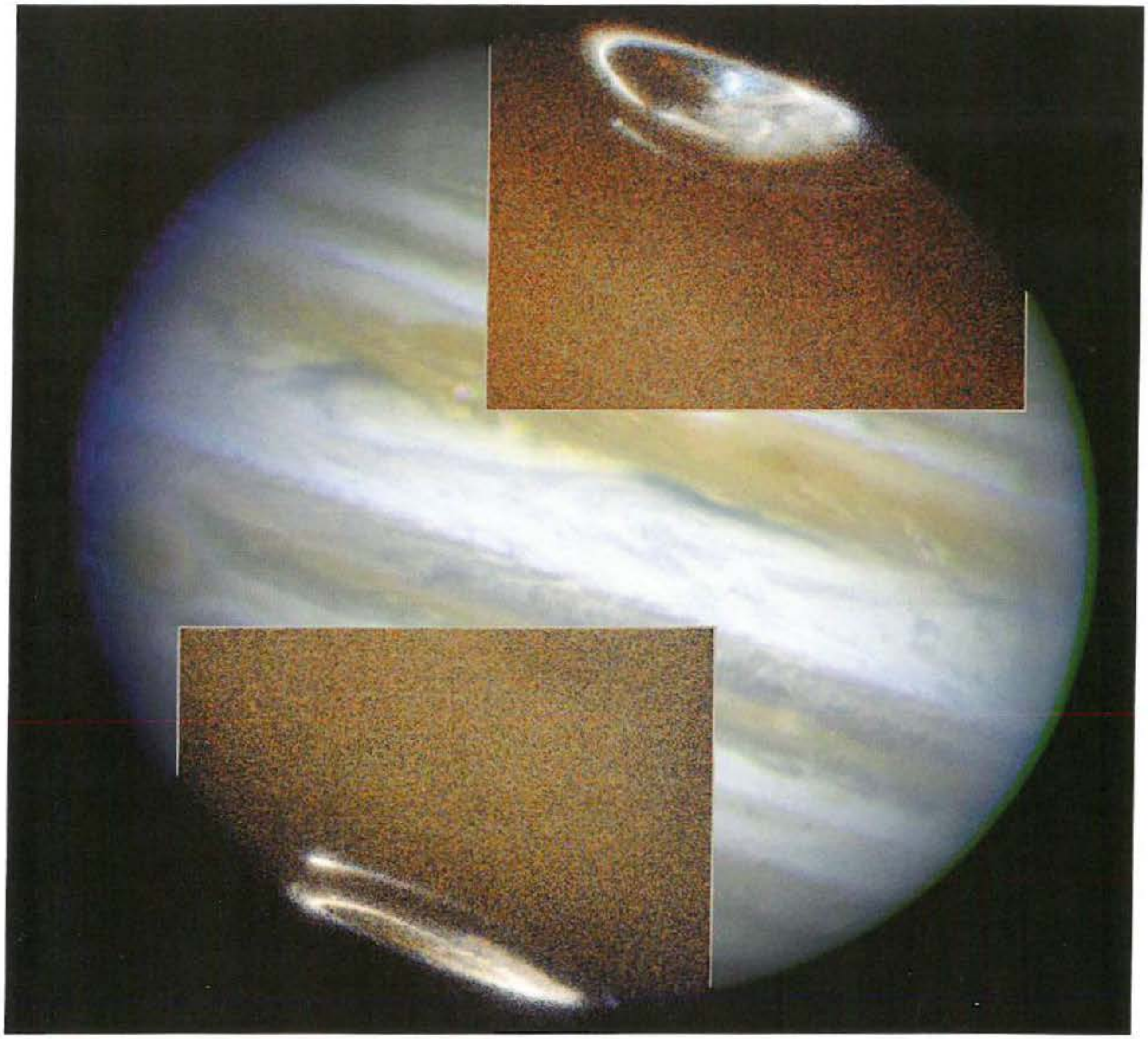


Figure 16. **High-energy electrons cascade into Jupiter's upper atmosphere and create bright auroral displays at ultraviolet wavelengths. This composite image, taken by the Hubble Space Telescope in September 1997, clearly shows auroral ovals in both the northern and southern polar regions. Elongated trails outside the ovals mark the locations where the powerful electrical current sheets from Io enter the Jovian atmosphere.**

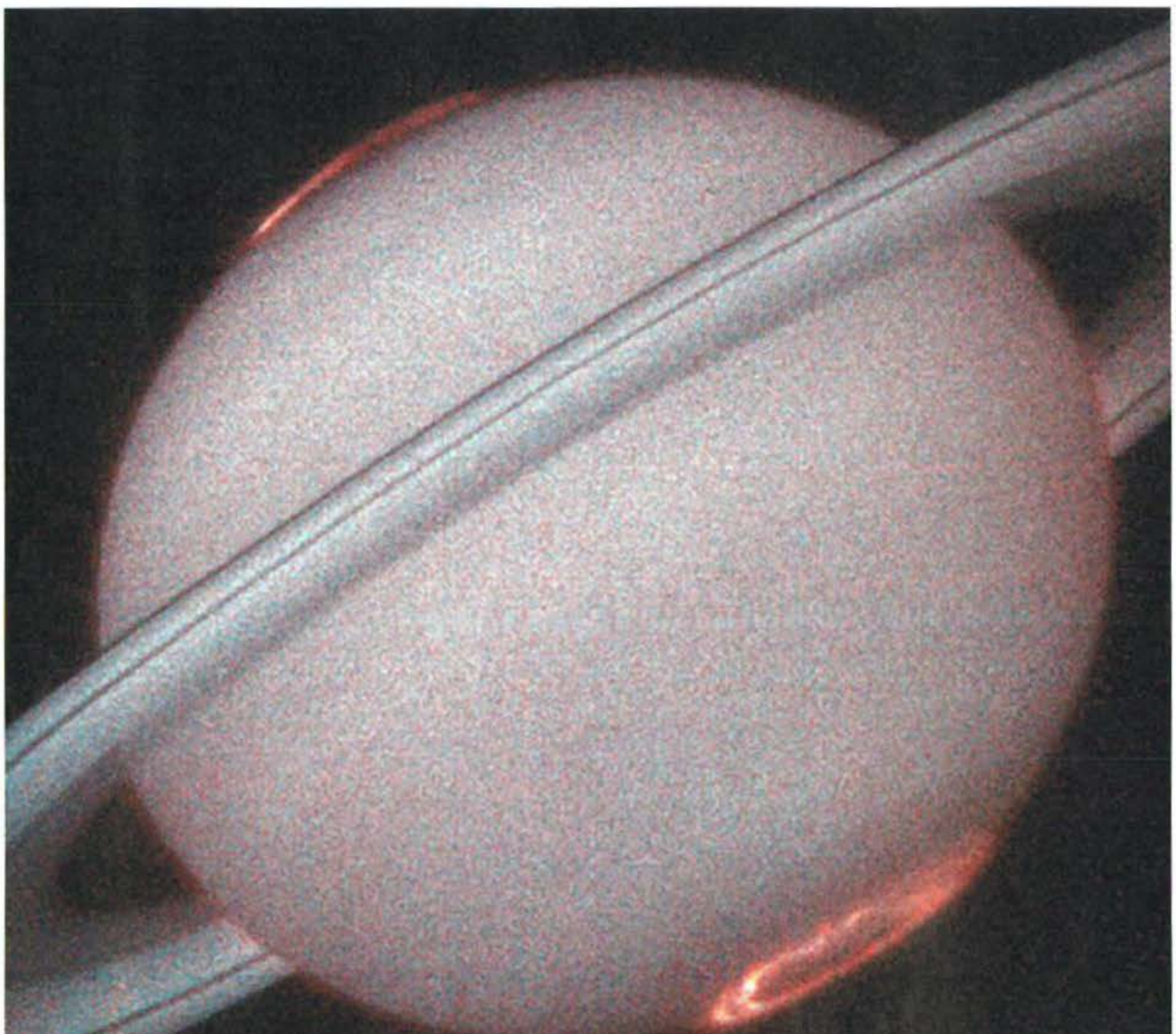
On returning to the outer region of the torus, these energetic ions and electrons are redirected along the magnetic field into the atmosphere of Jupiter. The energy deposited by this process totals 10 to 100 trillion watts, and consequently it probably has an important influence on the temperature and dynamics of the polar regions of Jupiter's atmosphere. At the very least the process generates spectacular auroral emissions (*Figure 16*) whose surface brightness can exceed that of Earth.

The power for populating and maintaining the magnetosphere of Jupiter comes principally from the rotational energy of the planet and the orbital energy of Io, whereas the power source of Earth's magnetosphere is principally the solar wind. While rotation dominates the plasma flows throughout the day side of Jupiter's magnetosphere, it is clear that corotation cannot be maintained all the way down the tail. At some point the plasma begins to flow downstream, either as a steady wind or sporadically as *plasmoids* (similar to magnetic storms in Earth's magnetosphere). A copious amount of these energetic particles is discharged into interplanetary space. Galileo's excursions into the magnetotail should help us understand how this material is expelled. In a larger context, these data have gone far toward elucidating the origin of energetic charged particles in astrophysical settings like pulsars, which are often compared with Jupiter's giant rotating magnetosphere.

THE SYMMETRICAL SYSTEM OF SATURN

In contrast to the situation at Jupiter, prior to the arrival of spacecraft we knew nothing of the magnetic state of Saturn. No signature was apparent from Earth-based radio astronomy. Our speculations favored a strongly magnetized planet whose ring system prevented energetic electrons from being trapped close to the planet in synchrotron-emitting radiation belts. We suspected that an intense radiation belt existed outside of the outer edge of the main ring system.

Figure 17. **Saturn's auroras, like Earth's, are powered largely by ions and electrons captured from the solar wind. This ultraviolet image was recorded by the Hubble Space Telescope in October 1997.**



The discovery of Saturn's magnetosphere came in September 1979 as Pioneer 11 detected the presence of a bow shock 24 Saturnian radii (1.44 million km) from the planet's center on its sunward side. Soon thereafter, the spacecraft entered an intense, fully developed magnetosphere. As Pioneer 11 passed beneath the outer edge of the A ring, the instruments on board recorded a guillotinelike cutoff of the charged-particle population, as expected. The twin Voyager spacecraft followed soon thereafter, passing through the Saturnian system in November 1980 and August 1981.

These explorations revealed that Saturn's magnetic field is 600 times stronger than the magnetic moment of Earth but still considerably weaker than that of Jupiter. At first glance, the magnetosphere of Saturn can be thought of as a smaller version of the Jovian case, scaled down to 10 to 20 percent of its size. Both structures are dominated by rotation, satellites are the major sources of plasma, and centrifugal forces confine plasma to an equatorial disk. The major differences at Saturn, including the lack of synchrotron-emission belts, are due to the presence of large quantities of icy material in the rings, which efficiently absorb ions and electrons that strike them.

Low-energy ionized material permeates the Saturnian magnetosphere but at densities much lower than in Io's plasma torus. In addition to protons, the Voyagers found oxygen ions created by the dissociation and ionization of water molecules from the planet's rings and icy satellites. In 1993, Donald Shemansky and his colleagues used the Hubble Space Telescope to detect ultraviolet emission from OH molecules, which exist in a dense cloud that extends 30,000 km above and below the ring plane. To maintain this cloud, about 170 kg of water must be supplied by the rings every second. Neutral atoms and molecules outnumber charged particles by a factor of five to 10 throughout the magnetosphere. Saturn's is the only magnetosphere where neutral species are more abundant than ionized ones.

Another source of plasma is Titan, Saturn's largest satellite. It moves through the outer fringes of the magnetosphere at an orbital radius of 1.2 million km, or 20 Saturn radii. As discussed more fully later, Titan apparently loses nitrogen from its upper atmosphere to the fast-moving (corotating) magnetosphere and produces substantial plasma and magnetic effects in its wake.

In the inner magnetosphere, reactions between the plasma and the dense neutral cloud are the dominant source and loss processes. Outside about 10 Saturn radii, centrifugal force takes over and transports the plasma radially outward. The smaller scale of Saturn's magnetosphere and perhaps collisions with the dense neutral cloud seem to limit the generation of hot plasma, so the magnetosphere is not as inflated as that of Jupiter. Nevertheless, enough energetic particles precipitate into Saturn's atmosphere to produce bright auroral emissions (*Figure 17*).

Like their counterparts around Jupiter, the Saturnian satellites Rhea, Dione, Tethys, Enceladus, and Mimas are excellent absorbers of inwardly diffusing energetic electrons and protons. Yet, remarkably, the satellites selectively permit the inward migration of electrons at specific energies. Those electrons drifting in longitude at the same rate as a moving satellite are able to diffuse across its orbit as though the satellite were not present. Electrons with other energies, and thus drift rates, will most likely strike the satellite and be absorbed. Inside the orbit of Mimas, for example, nearly all of the surviving electrons have an energy of about 1.6 million electron volts. This selective effect is analogous to white light passing through a succession of colored filters. No similar phenomenon occurs in the magnetospheres of either Earth or Jupiter.

Inward-diffusing protons are less fortunate. They are strongly absorbed by Dione, Tethys, Enceladus, and perhaps dust in the tenuous E ring. Consequently, there is a near-total absence of low- and intermediate-energy protons within 180,000 km of the planet. Within 90,000 km of Saturn are protons with energies greater than 80 million electron volts and electrons having roughly 100 million electron volts. These potent charged particles could not have survived the gauntlet of inward diffusion from the outer magnetosphere; instead, they arise when cosmic rays interact with Saturn's upper atmosphere and ring material.

The count of all trapped particles drops dramatically at the outer edge of ring A, because they are absorbed by the ring material encountered there. In addition, Saturn's general magnetic field deflects most cosmic rays before they can reach the inner magnetosphere. As a result, the region interior to the A ring cutoff is nearly free of high-energy particles — it is the most completely shielded region of space within the solar system.

The imaging instrument on Pioneer 11 recorded an inner satellite first glimpsed from Earth in 1966 (since named Epimetheus) and discovered a previously unknown ring (F). Notably, the spacecraft identified both of these independently by the gaps they created in the magnetosphere's electron population. Pioneer 11 picked up other distinctive charged-particle absorption features, which were designated 1979 S3, S4, and S5. Fourteen months later Voyager 1 found another new ring, G, at the location matched by that of 1979 S3. The other two may be the signatures of as yet unconfirmed rings or small satellites.

ASYMMETRIC MAGNETOSPHERES

As Voyager 2 approached Uranus in January 1986, we wondered if our experiences with the symmetric magnetic environments of Earth, Jupiter, and Saturn would hold true for a planet that is quite literally spinning on its side. Pioneer 10 had already established that the solar wind extended beyond Uranus's orbit. An empirical relationship that relates the angular momenta and magnetic moments, the "Bode's law" of planetary magnetism, suggested that the magnetic moment of Uranus would be about one-tenth that of Saturn. Anticipation heightened in the early 1980s, when astronomers using the International Ultraviolet Explorer satellite observed "aurora-like" emissions from hydrogen in Uranus's upper atmosphere.

We knew that the rotational axis of Uranus would lie, in early 1986, within 8° of the planet-Sun line. If Uranus's magnetic and rotational axes were nearly parallel, as is the case for other magnetized planets, one magnetic pole would be pointed almost directly at the Sun and a very unusual magnetospheric shape would be expected. However, if the axes were inclined markedly to one another, each magnetic pole would move in a sweeping, conical path as the planet spun — creating an even more exotic magnetosphere.

Voyager 2 ended our many years of conjecture and sent magnetospheric theorists back to basics. The planet's magnetic moment is nearly the same strength as that predicted, but its orientation is *very* different from our expectations. Uranus's magnetic axis is tilted a huge 59° from the rotational axis and offset from the planet's center (*Figure 18*). As at Saturn, the presence of sizable satellites and a ring system controls the populations of charged particles in the inner magnetosphere. However, unlike the Saturnian situation, the diurnal wobble of Uranus's tilted magnetic equator creates a very complex relationship between the orbiting satellites and the magnetic field.

Uranus's magnetotail shows strong similarities to Earth's: two lobes with opposite polarities are separated by a cross-tail current and a flat layer of concentrated plasma. The plasma sheet lies in the magnetic equatorial plane near Uranus but bends parallel to the solar-wind flow about 250,000 km downstream. Unlike the situation at Earth, the whole tail structure rotates in space approximately about the Uranus–Sun line. This results from solar wind flowing in more or less along the Uranian spin axis.

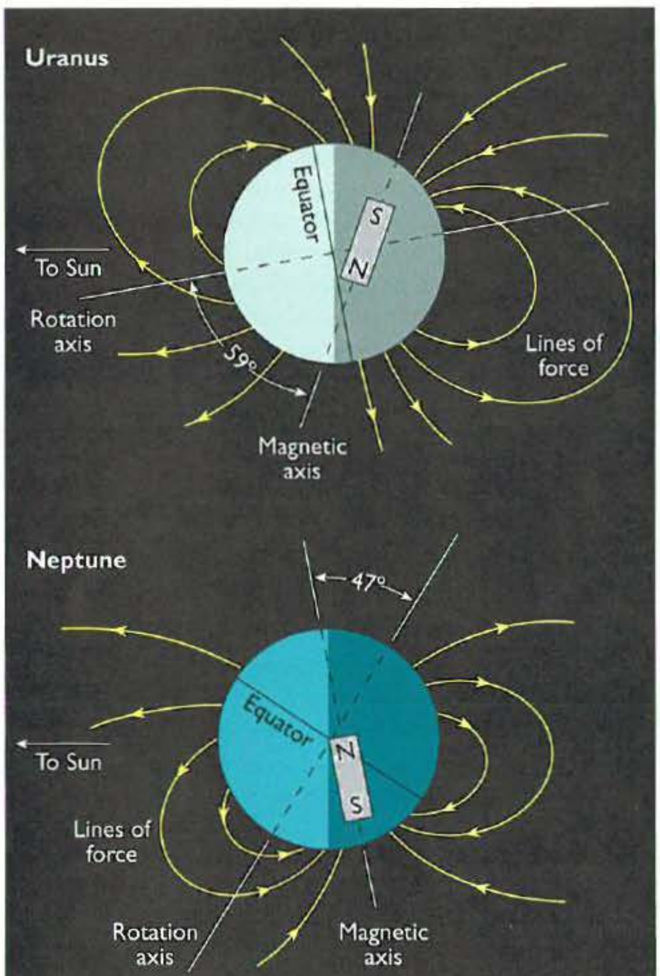


Figure 18. The magnetic fields of Uranus and Neptune are remarkably — and unexpectedly — alike. The large offsets from center means that the field strength at each planet's cloud tops varies widely from place to place. It also suggests that the field's source regions cannot lie in the cores but rather in a turbulent liquid mantle where dynamo-driving convection can be sustained.

Essentially, the solar wind is now approaching the planet from "over the pole." Thus, although the trapped plasma corotates with the planet once every 17 hours, over time it is circulated through the magnetosphere by solar-wind–driven convection. In some circumstances the particles trace out helical trajectories, spiraling sunward at the magnetic equator and antisunward at high latitudes. Within about 100,000 km of the planet, solar-wind convection is ineffective, allowing appreciable amounts of cold plasma to accumulate. Farther out, convection stirs up a plasma with higher energies, in the range of 1,000 electron volts. Voyager 2 found that this hotter population is almost completely absent from the inner, cold-plasma region. However, the Voyager data also recorded pulses of activity, akin to Earth's magnetic storms, that appear to propagate inward from the magnetotail.

Two factors make Uranus's magnetosphere rather empty: there are only a few, small icy satellites, and solar-wind convection circulates material through the magnetosphere in a few days. Voyager 2 found the plasma to consist almost entirely of protons. The dearth of heavier ions (specifically oxygen) means that water molecules are not sputtering off the icy satellites in profusion. The cold (low-energy) plasma probably arises from hydrogen atoms in Uranus's upper atmosphere and protons flowing out of the ionosphere. The hot plasma may derive from hydrogen atoms that become ionized farther out; they attain higher energies because corotational speeds increase farther from the planet.

Unfortunately, Voyager 2's pass through the complex and variable Uranian magnetosphere was too brief to pin down even the basic properties such as the dominant source of its plasma. Nevertheless, we offer one simple prediction: the magnetosphere's configuration will change radically during the next phase of the planet's 84-year orbit as the rotational pole swings away from the solar-wind direction. For example, early next century, the solar wind will impinge at latitudes close to the rotational equator. Tilted from the spin axis by 59°, the magnetic pole will gyrate toward and away from the solar wind every 17 hours (Uranus's spin period), creating a magnetospheric configuration similar to that found at Neptune.

In its fourth and final planetary flyby, Voyager 2 reached Neptune in August 1989. The spacecraft found a magnetic field substantial in strength, inclined 47° to the rotation axis, and having a large offset from center (*Figure 18, Table 1*). At the time of the encounter, Neptune's northern hemisphere was in mid-winter, tipped 23° away from the Sun. The large tilt of the magnetic dipole means that the angle between the solar wind and the dipole axis was vacillating between 20° and 114° during each 16.1-hour Neptunian day (*Figure 19*). When the angle is near 90° the configuration is, momentarily, symmetrical — like that of Earth, Jupiter, and Saturn. When the angle is small, however, the magnetic axis points "pole-on" into the solar wind (the configuration that we expected for Uranus before Voyager 2 discovered otherwise). Consequently, the magnetic field and magnetosphere appear to gyrate wildly as seen from outside the system.

The dramatic changes in geometry make it difficult to visualize the behavior of trapped plasma. Corotation again plays the dominant role, though convection driven by the solar wind has a cumulative effect over several planetary rotations.

The maximum coupling between the solar wind and the magnetosphere occurs for the "Earthlike" configuration. According to one model, at such times plasma situated on the day side at local noon will drift away from Neptune, while plasma on the midnight line will drift (more slowly) toward the planet. Thus, the plasma spirals inward or outward depending on its location at the time of Earthlike configuration. A second model envisions a four-cell convection pattern that corotates with the planet.

The dramatic changes that occur in the configuration of the magnetotail during every planetary rotation must further complicate the dynamics of Neptune's magnetosphere. During the Earthlike magnetic configuration, the magnetotail mimics Earth's tail, with lobes of opposite polarity separated by a current sheet. When the magnetosphere is pole-on to the solar wind, the magnetotail has a cylindrical shape. At such times, the magnetic-field lines directed toward the planet are on the outside of the cylinder. Field lines leaving the planet are on the inside, and a cylindrical current sheet separates them.

Neptune's large satellite Triton orbits well inside the magnetopause, and every second it supplies an estimated 10^{25} ions (200 g) of nitrogen into the surrounding magnetosphere. The N^+ ions detected by Voyager 2 are likely produced when magnetospheric plasma collides with the satellite's atmosphere, while the protons come from a large, diffuse hydrogen cloud that extends from Triton's orbit inward for more than 150,000 km. Closer in, much of the plasma is absent, apparently redirected by magnetospheric waves along the magnetic field and into the atmosphere of Neptune. However, this simple picture is not without its problems, and we know that considerable further study is required in order to understand the plasma configuration and dynamics of Neptune's magnetosphere.

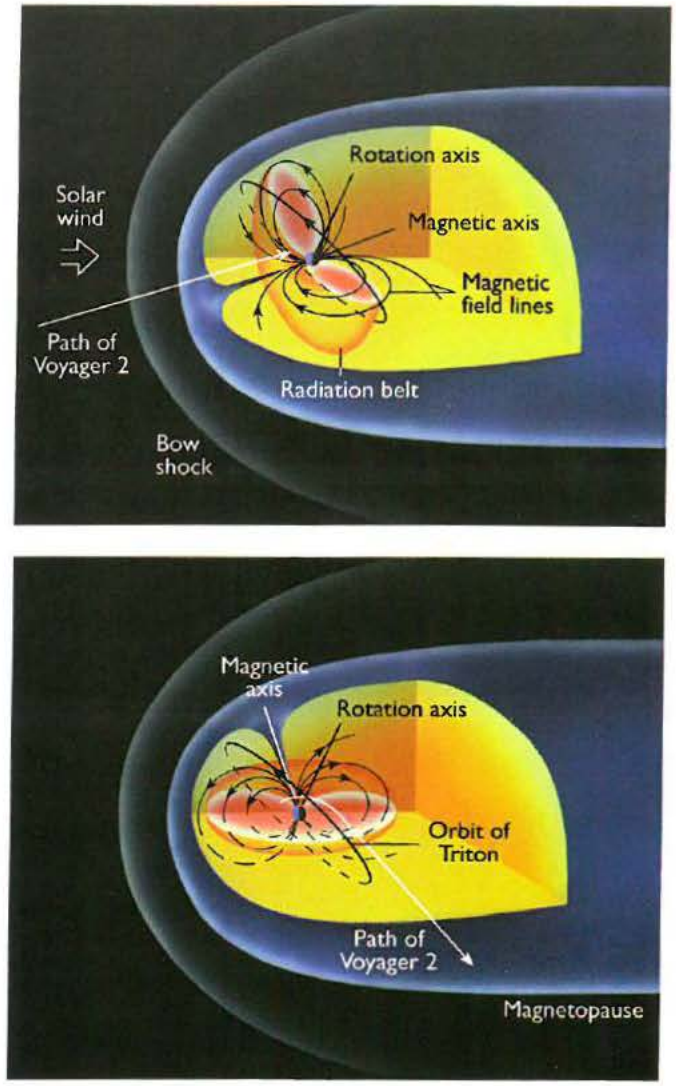


Figure 19. **All of Neptune's rings and satellites (except Nereid) lie deep within the planet's largely empty magnetosphere. When Voyager 2 crossed the magnetopause on 24 August 1989 (upper panel), one pole of Neptune's highly inclined magnetic field was pointing toward the Sun. When the spacecraft made its exit 38 hours later (lower panel), the field's orientation was very different and rather Earthlike.**

SMALL MAGNETIZED WORLDS

Before 1974, it was thought that only large planets would have magnetic fields and that convective motions in smaller objects would have halted as the interiors cooled. The discovery of weak but significant magnetic fields of smaller bodies, first Mercury and recently Ganymede, has challenged our view of both the dynamo process and the nature of small-scale magnetospheres.

Mercury. During 1974 and 1975, the Mariner 10 spacecraft made three successive flybys of Mercury, providing the first and thus far only close-up observations of the innermost planet (see Chapter 7). Mercury takes 59 days to rotate, which might seem too slow to sustain dynamo activity. Nonetheless, the planet has a distinct though weak global magnetic field with a magnetic moment $1/1400$ that of Earth. Before Mariner 10, geophysicists suspected that Mercury's core should be completely solid. However, the presence of a magnetic field shows that at least a shell of molten material must still exist (perhaps iron mixed with sulfur to lower its melting point), and that it must be in convective motion.

The magnetosphere of Mercury contains closed field lines (that is, connected to the planet at both ends), but the field is too weak to maintain a belt of trapped particles. Low-energy plasma was detected by the Mariner spacecraft's traversals through the nightside magnetosphere, but we are uncertain whether this plasma originates in the solar wind or from the ionization of Mercury's tenuous atmosphere (see Chapter 13). More notable, however, are the intense bursts of energetic particles detected in the magnetotail. These have been compared with magnetic substorms on Earth and suggest that Mercury's magnetosphere is dynamic. The Mercurian storms last about 1 minute (compared with hours at Earth), consistent with the much smaller scale of the planet's magnetosphere.

Ganymede. One of the greatest surprises of the Galileo mission was the discovery of a magnetic field intrinsic to the Jovian moon Ganymede. This creates a magnetosphere within a magnetosphere (*Figure 20*), the first of its kind found in a planetary system.

The Jovian plasma, in which Ganymede is embedded, flows at speeds much slower than the solar wind and, in particular, slower than the local speeds of waves that propagate in the magnetospheric plasma. It is a subsonic flow, hence no bow shock occurs upstream of Ganymede. We suspect that there is a small region close to the moon where magnetic field lines are closed. However, the magnetosphere of Ganymede is too small to have trapped plasma or a magnetotail. There is thought to be a pattern of convection, similar to solar-wind-driven convection at Earth, but in this case driven by the interaction of Ganymede's magnetic field with the magnetospheric plasma sweeping past it.

Orbiting Jupiter at a distance of 19 Jovian radii, Ganymede is located in the middle magnetosphere region. Consequently, the moon experiences a change in the surrounding plasma conditions and magnetic-field orientation as the tilted plasma sheet passes over the satellite twice per 10-hour rotation.

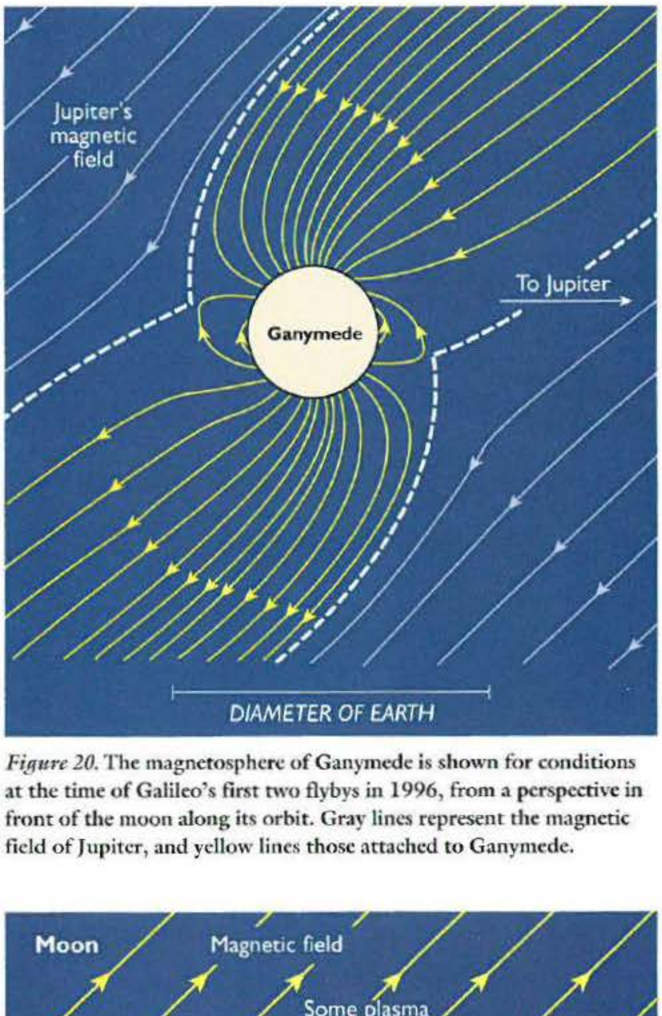


Figure 20. **The magnetosphere of Ganymede is shown for conditions at the time of Galileo's first two flybys in 1996, from a perspective in front of the moon along its orbit. Gray lines represent the magnetic field of Jupiter, and yellow lines those attached to Ganymede.**

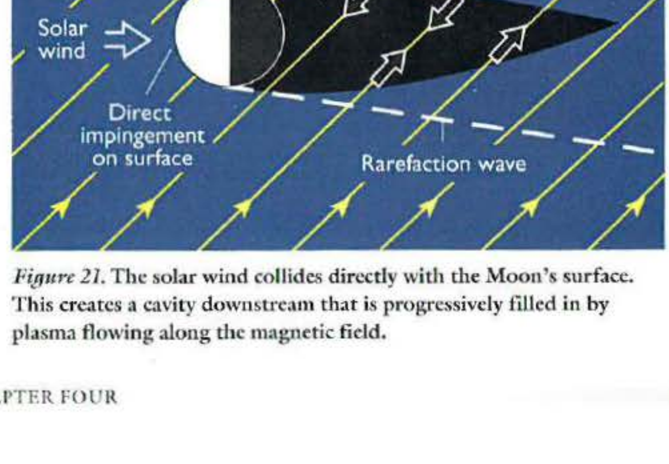


Figure 21. **The solar wind collides directly with the Moon's surface. This creates a cavity downstream that is progressively filled in by plasma flowing along the magnetic field.**

On Galileo's passes over Ganymede's magnetic poles, plasma detectors measured a substantial outflow of protons. These may result from the photodissociation of water vapor that has sublimated from the moon's icy surface (or has been sputtered off it by charged particles). The fact that no oxygen ions were detected suggests that the oxygen must be left behind on the surface.

PLASMA INTERACTION WITH ROCKS

Earth's Moon. The first extraterrestrial body to be investigated firsthand was the Moon, an object studied intensively by many American and Soviet flybys, orbiters, and landers. Yet the Moon has no global magnetic field — its magnetic moment is at least 10 million times weaker than Earth's. The Moon must therefore lack the convecting molten core necessary for an internal dynamo. Models of the lunar interior suggest that the core is small and at least partially solidified. Curiously, experimenters have discovered *localized* regions on the Moon with surface magnetic fields of 5 to 300 nT, but these appear to be geologic anomalies exhibiting remanent magnetization that has survived from long ago. How the primordial Moon could have developed such magnetized patches remains a nagging problem.

Our satellite passes through Earth's magnetotail a few days each month near the time of full Moon; for the remainder of the month it is outside the magnetosphere and immersed in the solar wind. Because the Moon lacks both a global magnetic field and a significant atmosphere, the solar wind strikes the lunar surface directly and some of its particles become infused into the rock and dust there. For example, the Apollo lunar samples contained significant amounts of trapped helium-3, an isotope that holds considerable promise as a fuel for fusion-powered energy systems. Extending from the Moon's antisolar side is a long plasma void (or plasma umbra) shaped like an ice-cream cone, with its apex downwind and with the Moon itself as the scoop of ice cream (*Figure 21*). Although this void gradually fills in farther downstream because of the lateral motion of solar-wind particles, it still may be one of the most nearly perfect vacuums in the solar system.

The existence of such a plasma void implies a system of weak electrical currents along its boundary; these currents were observed during the late 1960s by the lunar-orbiting spacecraft Explorer 35. In addition, the varying magnetic field entrained in the solar wind induces a system of transient electrical currents within the Moon itself, as was observed by the long-lived Apollo magnetometers placed on its surface.

Europa and Callisto. Compared with the strong interaction at Io and the magnetosphere of Ganymede, results from the initial Galileo flybys of Europa and Callisto were rather disappointing. Neither moon shows strong magnetic signatures, putting weaker upper limits on their surface fields of 30 nT for Callisto and 240 nT for Europa. These results pose interesting problems for planetary scientists. Why do the similar-sized Ganymede and Callisto have such different interiors? Furthermore, should Io's magnetic field be confirmed, why doesn't Europa have a dynamo? After all, Io and Europa have very similar interiors (see Chapters 17–19).

The Galileo particle and field data from the first few flybys of Europa and Callisto are puzzling. They show complex structure that does not fit the simple picture exemplified by the solar-wind interaction with the Moon. The signatures imply that magnetic fields are being induced in a conducting layer within each body by Jupiter's magnetosphere. Since both moons are largely ice, the most plausible conductors are subsurface oceans of water (see Chapter 18 and 19).

Asteroids. The small sizes of asteroids imply that they should have very little interaction with the solar wind beyond unimpeded bombardment by charged particles. However, the significant perturbations of the interplanetary magnetic field measured during Galileo's flyby of 951 Gaspra in October 1991 changed this view. Margaret Kivelson and her colleagues estimate that Gaspra could have a level of magnetization, presumably remnant, comparable in strength to that found in chrondritic meteorites. A similar, though rather weaker signature was observed when Galileo flew past 243 Ida in August 1992. Because an asteroid is smaller than the diameter of the gyrations that solar-wind protons make in the interplanetary magnetic field, the waves generated by the asteroid's interaction propagate faster than the solar wind itself. This means that no bow shock forms upstream of these asteroids. Their interaction regions are wedge shaped, similar to a wake of a ship.

PLASMA INTERACTION WITH ATMOSPHERES

The scale of the interaction between a flowing plasma and the atmosphere of a nonmagnetic planet depends on the atmosphere's thickness. At one extreme is Mars, whose tenuous ionosphere is barely able to hold off the solar wind. At the other extreme is the case of a comet near perihelion. Its "atmosphere" extends for hundreds of thousands of kilometers. The circumstances for Venus and Titan lie near the middle of these extremes. Pluto's situation could range anywhere from a weak Marslike interaction to that of a comet. Among all these, we have the most information about Venus.

Venus. American and Soviet spacecraft have observed the magnetic properties of Venus for nearly four decades. The planet's magnetic moment is undeniably weak, at least 25,000 times less than Earth's, despite our sister planet's comparable size and probable molten interior. The lack of a comparable magnetic field suggests Venus lacks the temperature gradient and vigorous internal convection required for a dynamo. Nonetheless, the solar wind is prevented from reaching the surface by Venus's dense atmosphere and by electrical currents induced in its conducting ionosphere. The barrier that separates the planetary plasma from solar-wind plasma is referred to as the ***ionopause***. The planet has a well-developed bow shock, but it possesses no population of trapped particles.

When it reaches Venus, the solar wind slows down and is deflected around the ionopause (*Figure 22*) and the interplanetary magnetic field is draped back to form a magnetotail. Sometimes the magnetic field lines become concentrated into a twisted bundle like a rope, and these "tubes" of magnetic flux are dragged through Venus's ionosphere. Oxygen and hydrogen atoms in the planet's extended atmosphere become ionized and picked up by the solar wind. Many of these ions come bom-

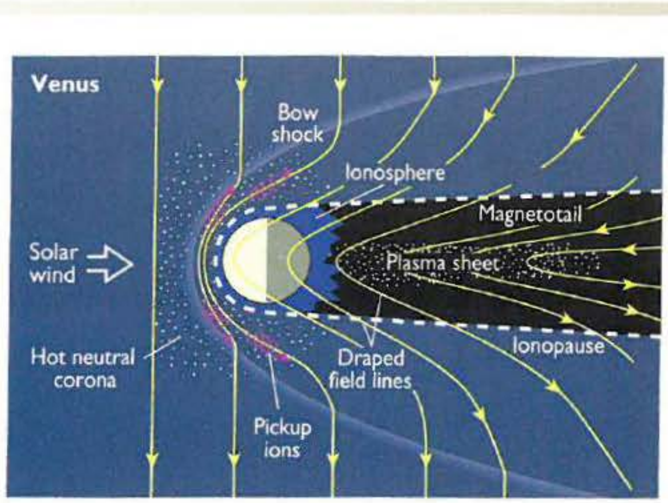


Figure 22. **Even though it has no intrinsic magnetic field, Venus still interacts with and diverts the solar wind by virtue of its ionosphere and extended corona of hot gas derived from the upper atmosphere.**

barding back into the atmosphere, further heating its uppermost layers. The rest are carried away by the solar wind. The present removal rate (10^{26} O^+ ions per second) is too low for this process to be a significant factor in the lack of water in Venus's atmosphere.

The solar wind's interaction with Venus changes on time scales of hours, depending on the wind's dynamic pressure and the orientation of the interplanetary magnetic field. Over the course of an 11-year solar cycle, variations in the solar wind and in the Sun's ultraviolet and X-ray output dramatically change the heating and ionization of Venus's upper atmosphere and hence the size of the interaction region.

Mars. Until the recent Mars Global Surveyor mission, sparse data from Mariner 4 (1965) and the Soviet orbiters Mars 2, 3, and 5 (1971–1974) and Phobos 2 (1989) represented our only observations of the magnetic properties of Mars. The upper limit on an interior dipole magnetic field is about 30 nT at the planet's equator. This magnetic moment is at least 5,000 times weaker than that of Earth. Nonetheless, the planet's ionosphere deflects the solar wind and the interplanetary magnetic field is draped around the ionopause, forming a magnetotail downstream. There are a weak bow shock and plasma phenomena similar to the interaction at Venus. The tenuous atmosphere of Mars implies that the ionosphere is tenuous too and perhaps insufficient to stand off the solar wind alone. In that case a very weak internal field might prove necessary. Alternatively, if the ionosphere of Mars were only weakly conducting, the interplanetary magnetic field would be able to penetrate into the ionosphere region, where it would pile up (since the accompanying plasma flow is slowed down) and be able to provide additional pressure to hold off the solar wind.

Mars Global Surveyor detected patchy crustal magnetization of up to 400 nT, which is comparable to the remnant magnetization measured in some of the meteorites that are believed to have been ejected from Mars. Conceivably, if enough of the surface exhibits similar levels, the total magnetic field may have a significant effect on the solar-wind interaction.

Phobos 2 detected abundant O^+ that had been ionized in Mars's upper atmosphere and picked up and carried away by the solar wind. The observed rates of escape (10^{25} oxygen ions and

10^{24} protons per second) suggest that this scavenging could have played a significant role in the evolution of the Martian atmosphere over the age of the planet — or at least since the decay of any internal dynamo.

The global magnetic field of Mars is too weak and the atmosphere too thin to protect the planet's surface from cosmic rays and bursts of solar-flare protons. Even if Mars had an active dynamo 1.3 billion years ago (when most of the known Martian meteorites crystallized), the field that may have induced the remnant magnetization now found in the meteorites was also weak, no more than 1,000 nT and thus comparable to Mercury's current field. Consequently, any biogenic materials present on the planet's surface must have been exposed to high doses of radiation.

Titan. The single flyby of Titan by Voyager 1 in November 1990 recorded an intriguing plasma-atmosphere interaction, the further study of which is a major objective of the Cassini/Huygens mission. The spacecraft's measurements suggest that the background magnetic field of Saturn is draped over Titan and forms a magnetotail downstream. The upper limit on the internal field of Titan is about 4 nT at the surface, implying a magnetic moment no greater than 0.00001 of Earth's.

Saturn's largest moon is similar in size to the Galilean satellites, but its dense nitrogen-methane atmosphere sets it apart from all other satellites (see Chapter 20). The combination of high surface pressure (about 1.5 bars) and low gravity (about 15 percent of that on Earth) results in an atmosphere that extends far above the surface. Its exobase is 1,400 km up — one-fourth of the moon's diameter. Solar ultraviolet light and electrons from Saturn's magnetosphere heat this extended upper atmosphere, driving off about 10 kg of neutral nitrogen and hydrogen atoms per second. This is comparable to the gas lost by an active comet.

Solar ultraviolet light and magnetospheric electrons also ionize Titan's upper atmosphere (particularly on the nightside) and produce a complex mix of ions. The resulting dense ionosphere is probably sufficient to deflect the tenuous plasma present at

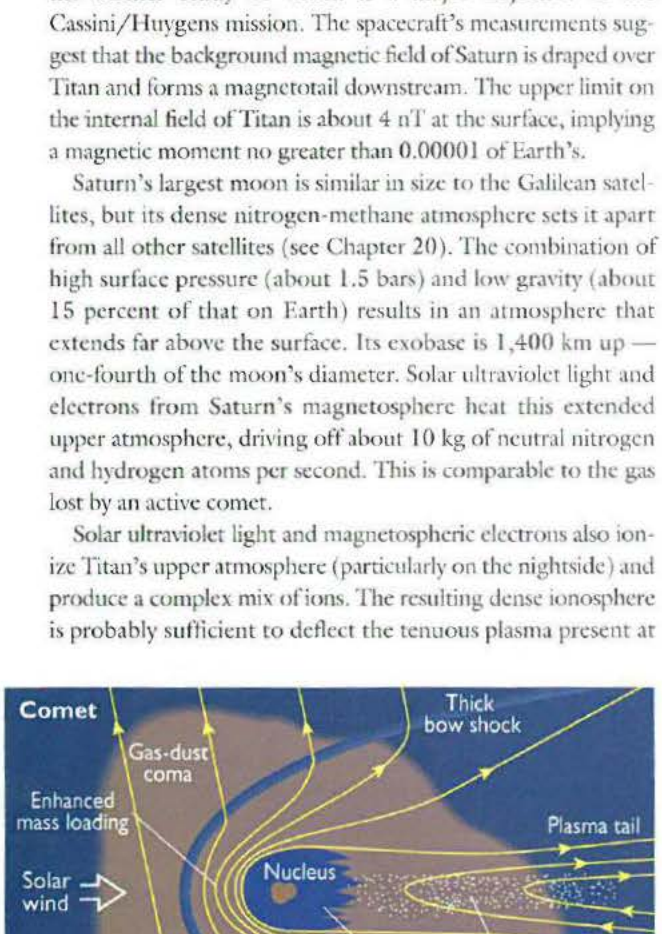


Figure 23. **The gas lost from a comet's nucleus is quickly ionized by sunlight, creating a planet-scale obstacle to the solar wind. This portrayal of the complex interaction is not to scale: the nucleus is typically just a few kilometers across, whereas the cometopause is about 10,000 km to its sunward side and the bow shock about 1 million km away.**

Titan's location in the outer Saturnian magnetosphere. Thus, in many ways Titan's situation mimics how solar wind interacts with Venus, except that the uppermost layers of Titan's neutral atmosphere can be scavenged directly by the plasma flowing by. About 30 g per second is lost in this way.

Comets. The icy nuclei of comets are presumably not magnetized. However, as they pass through the inner solar system these objects create huge envelopes of escaping gases, which become ionized and interact with the solar wind (*Figure 23*). Indeed, as mentioned earlier, Ludwig Biermann's observations of the ionized-gas tails of comets provided the first evidence for the continuous nature of the solar wind.

The Sun causes both solar-wind pressure and radiation pressure (the latter from the "impact" of photons of light) on all objects in the solar system. For something the size of an asteroid or planet, these pressures have a negligible effect compared to gravitational forces. For cometary dust grains, which have vastly greater area-to-mass ratios, radiation pressure is quite important. Conversely, the solar wind has a much greater effect on ionized cometary gas than radiation pressure does. Comets' ionized tails are thus distinguished from their more familiar dust and neutral-gas tails by their form, optical spectra, and other detailed features (see Chapter 24).

The interaction process starts where the solar wind first picks up cometary ions, millions of kilometers from the nucleus. These ions not only slow down the solar wind but also create waves in the plasma that are ultimately responsible for the surprisingly abundant energetic particles detected at comets. After passing through a bow shock, the solar-wind plasma continues to slow down as more and more cometary ions are picked up from the increasingly dense "atmosphere" (coma). The deceleration of the solar wind causes the interplanetary magnetic field to pile up and drape around the comet's ionosphere, forming an extended magnetotail behind it. At Comet Halley, the Giotto spacecraft detected a well-defined boundary that separated the mixture of solar wind, cometary plasma, and interplanetary magnetic field from the field-free, nearly pure cometary ionosphere. This ionopause can be up to 20,000 km across, providing an area some 10 times larger than Venus's ionopause. Therefore, it is not surprising that a small comet can provide thousands of times more ions to interact with the solar wind than Venus can.

Pluto. While it is improbable that Pluto has an internal magnetic dynamo, even a little remanent magnetization could produce a significant magnetosphere in the weak solar wind 30 to 50 AU from the Sun. A surface field of 1 nT would be enough to stand off the solar wind from the surface, while 3,700 nT would produce a magnetosphere large enough to encompass Charon's orbit. Such surface fields could easily exist if Pluto retains a magnetization comparable to that of chondritic meteorites.

Pluto's atmosphere is only weakly bound to the planet, and an estimated 10^{27} to 10^{28} molecules per second may be escaping to space. For typical solar wind conditions at 30 AU, escape rates significantly greater than 1.5×10^{28} molecules per second slow the solar wind and create a cometlike interaction that might extend beyond the orbit of Charon. If the escape rate is less, then the estimated density of electrons should be sufficient to create an ionopause about 600 km above Pluto's sunlit hemisphere. In this case, the interaction would be like that of Mars. The large variations in solar-wind flux that have been observed in the outer heliosphere suggest that the stand-off distance would vary from about 4 to 24 Pluto radii on time scales of days.

However, the nature of the solar-wind interaction would change dramatically if Pluto's atmosphere were to freeze out as the planet recedes from the Sun after perihelion. Around aphelion, both Pluto and Charon would simply absorb the solar wind on their dayside hemispheres (if Pluto is unmagnetized), similar to the situation with Earth's Moon.

THE HELIOPAUSE AND BEYOND

We now believe that the solar wind merges with the nearby interstellar medium and loses its identity roughly 100 AU from the Sun (*Figure 24*). The boundary at which this merging begins is called the *heliopause* and the region inside it the *heliosphere*. Instruments on Pioneer 11 made significant contributions to this subject until tracking of the spacecraft ended in January 1995 at a heliocentric distance of 42 AU. Pioneer 10 continues to provide valuable cosmic-ray observations from its location more than 70 AU from the Sun. Voyagers 1 and 2, respectively 70 and 55 AU from the Sun in mid-1998, continue to function well as they head out of the solar system at more than 3 AU per year.

Moving outward from the Sun, the average increase in total cosmic-ray intensity measured by these spacecraft is 1.3 percent per AU, and the outer boundary is now known to lie beyond 70 AU (Pioneer 10). This cosmic-ray modulation boundary is doubtless related to the termination shock and heliopause but may not be identical to either.

In May and June 1991 a series of extraordinarily intense blast waves originated at the Sun. About 400 days later correspondingly strong bursts of radio waves were received by both Voyagers. Donald Gurnett has interpreted these events as evidence for the terminal shock being about 110 AU away and the heliosphere about 145 AU. Both distances probably fluctuate by tens of AU as the dynamic pressure of the solar wind varies with the level of solar activity. Direct observations of these transition regions by Voyager 1 are eagerly awaited. This craft's passage out into the interstellar medium will be revealed by at least three effects. First, the solar wind, flowing radially outward, will be replaced by an interstellar wind of different speed, ionic composition, temperature, and direction of flow. Second, the intensity and spectrum of the cosmic radiation will become constant, no longer modulated by the magnetic irregularities of the solar wind. (This expectation assumes that the interstellar medium

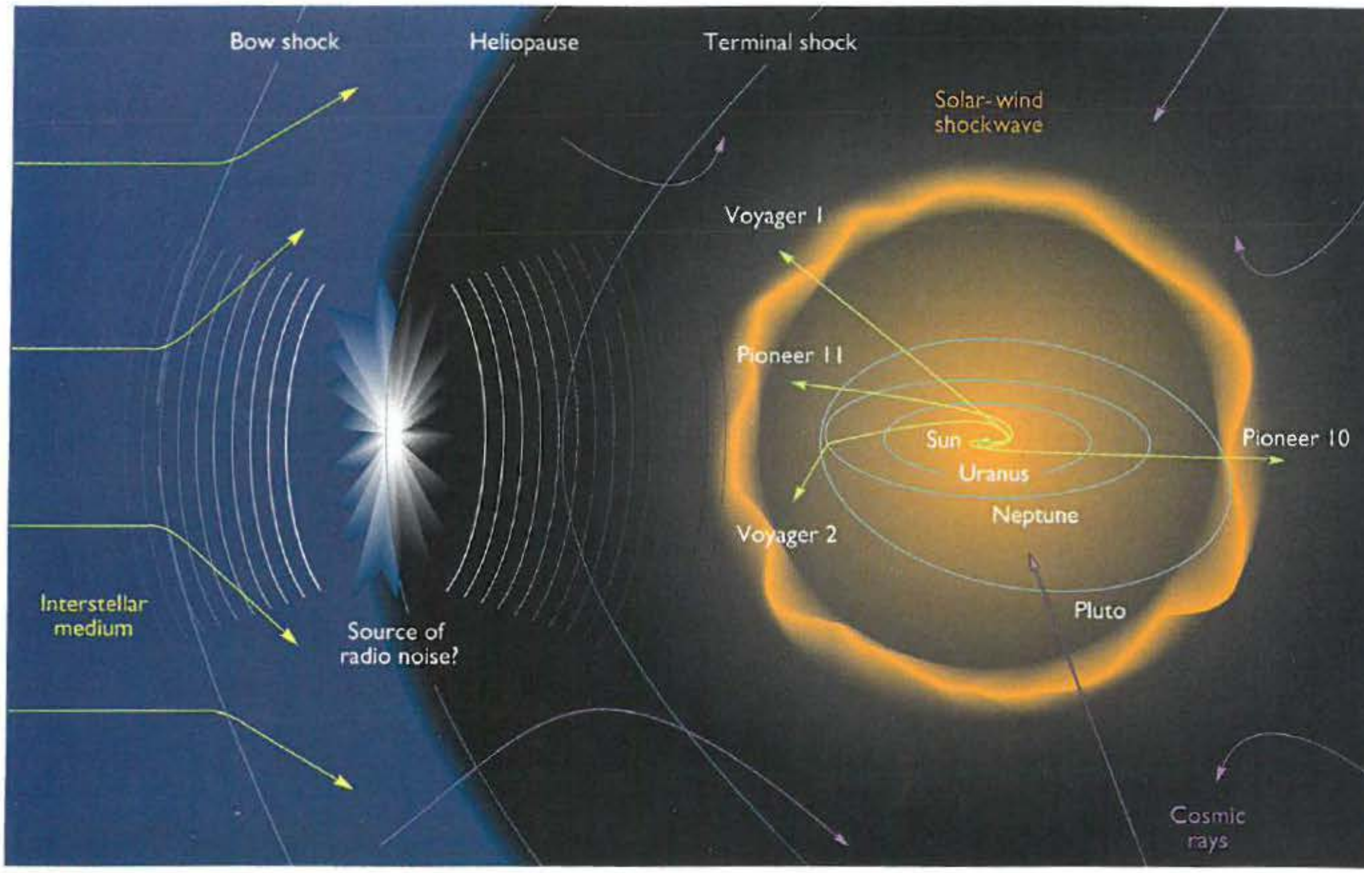


Figure 24. **Space physicists believe the Sun's electromagnetic influence extends to a distance of roughly 150 AU, far beyond the orbit of Pluto. There, at what they term the heliopause, the outward-flowing solar wind meets the interstellar medium. Neither the termination shock, the heliopause, nor the bow shock has yet been directly observed. However, space scientists believe a dense, high-speed shell of plasma ejected by the Sun in mid-1991 reached the heliopause in late 1992 and triggered a massive release of radio energy that was detected by both Voyager spacecraft.**

contains a smoothed average of contributions for many extremely remote sources.) Third, the total cosmic-ray intensity will be greater than that at any point within the heliosphere. In addition, the local signature of the transition region may be detectable by the spacecraft's magnetometer and plasma-wave instrument.

Voyager 1's instruments are already near their limits of sensitivity for making such measurements. On the other hand, since relatively low-energy cosmic rays become more abundant farther away from the Sun, observations of such particles may offer the best potential for revealing the location of the heliopause. Even so, the transition to the interstellar medium may occur not at an exact distance but over perhaps many AU and at a mean distance that fluctuates with the 11-year cycle of solar activity.

The solar system does not end at the heliopause, however. In recent years dozens of small bodies have been discovered on the outer fringes of the heliosphere. These objects are thought to be relatively primitive, remnant icy planetesimals that condensed on the very fringes of the solar nebula or were kicked out by the giant planets. While their interiors may have remained unaltered, their surfaces have been bombarded by the solar wind or the interstellar medium for billions of years. Over such long periods even low-level radiation exposure can substantially change the chemical and optical properties of the surface materials. Unfortunately, close-up exploration of even the nearest Kuiper-belt objects will be decades in the future. In the meantime, studying the interaction of the solar wind or magnetospheric plasmas with satellites, asteroids, and comets closer to Earth will help us to understand the different surface processes at work and to interpret the spectroscopic signatures from more distant and presumably more primitive surfaces.

The application of knowledge derived from magnetospheric physics to the study of the radio, X-ray, and gamma-ray emissions from distant objects is already an active field that will likely play an increasingly important role in modern astrophysics.