

MAGNETOSPHERES OF THE OUTER PLANETS

The Voyager explorations of the outer solar system have revealed that the magnetospheres of the outer planets interact strongly with embedded moons and rings. The implications of these interactions are discussed for Jupiter, Saturn, and Uranus.

INTRODUCTION

Initial explorations of the giant planetary systems in the outer solar system are being carried out by four unmanned spacecraft. The Pioneer 10 and 11 spacecraft were the first to encounter the Jovian system in 1973 and 1974, respectively, and Pioneer 11 continued on to make the first exploration of Saturn in 1979. Voyagers 1 and 2 encountered Jupiter in 1979 and Saturn in 1980 and 1981, respectively. Both Pioneer spacecraft and Voyager 1 continue to return data from the outer solar system but will make no further planetary encounters. Pioneer 10 has traveled farther from the sun than any other man-made object and is currently at a distance of nearly 40 astronomical units. Voyager 2 made the first exploration of the Uranian system in January 1986 and is expected to make the first exploration of Neptune in August 1989. These explorations of the outer solar system will surely be remembered as one of the great triumphs of our time.

The many wonders of the Jovian and Saturnian systems as revealed by the Pioneer and Voyager spacecraft have already been summarized in several books¹⁻⁴ and more than a thousand technical articles. Our knowledge and understanding of the interiors, atmospheres, magnetospheres, satellite systems, and ring systems of the giant planets have been completely transformed. The scope of modern planetary science is too vast to be encompassed within this brief review, and I will discuss only one subject in which I personally have been involved: the interaction of planetary magnetospheres with the surfaces and atmospheres of the planets, satellites, and ring particles. This work is only one of many investigations performed by members of the Low Energy Charged Particle (LECP) experiment team led by S. M. Krimigis.⁵⁻⁷ The experiment was built by APL and flown on Voyagers 1 and 2 to measure ion and electron fluxes from about 30,000 to above several megaelectronvolts of energy.

Mercury, Earth, Jupiter, Saturn, and Uranus are the five planets known to have intrinsic magnetospheres; i.e., their planetary magnetic fields are strong enough to stand off the solar wind and create a cavity within it larger than the planets themselves. Within this cavity, or magnetosphere, the planetary magnetic field controls the dynamics of the charged particles. The solar wind is a tenuous ionized gas (a plasma), consisting mainly of

hydrogen and helium, that blows hypersonically away from the sun, carrying along the entrained solar magnetic field. The solar wind also makes a cavity within the interstellar medium that can be considered the magnetosphere of the sun (the so-called heliosphere⁸).

Charged particles can be trapped by the magnetic field within planetary magnetospheres since they spiral around magnetic field lines and are repelled by strong field regions. Because the magnetic field is strongest near the magnetic poles, charged particles can be trapped on field lines that extend from one magnetic pole to the other since they bounce off the high field region near one pole and then bounce off the high field region near the other. High-energy ions and electrons trapped on magnetic field lines in this way comprise the Van Allen belts at Earth. Similar radiation belts have been discovered at Jupiter and Saturn by Pioneers 10 and 11 and at Uranus by Voyager 2.

Among the outstanding problems in magnetospheric physics are the following: the identification of the sources of charged particles in the magnetosphere and the understanding of mechanisms by which they can be accelerated to the observed high energies (several tens to millions of electronvolts). It is obvious that charged particles can enter a planetary magnetosphere either from the outside (that is, from the solar wind) or from the inside. Potential internal sources of particles include the surface or atmosphere of the planet itself and any major moons or ring systems. It is in highlighting the importance of internal sources of plasma that Voyager results have had the greatest effect on our understanding of planetary magnetospheres; it is this issue that I will emphasize here.

JUPITER AND IO

Prior to the Voyager encounters with Jupiter, the prevailing view was that the dominant plasma sources in planetary magnetospheres were the solar wind and the planetary ionosphere. The solar wind is typically about 95 percent protons and 5 percent alpha particles by number, with all other species comprising much less than 1 percent. Jupiter's atmosphere is likewise dominated by hydrogen and helium and is about 90 percent molecular hydrogen and 10 percent helium by number. Indeed, very similar hydrogen- and helium-dominated compositions appear to be ubiquitous throughout the universe

and are known as “cosmic abundances.” They characterize not only the sun and solar wind but also all stars (except collapsed objects like white dwarfs and neutron stars), galaxies, the interstellar medium, and cosmic rays. The ubiquity of the cosmic abundances is believed to be a consequence of thermonuclear reactions following the Big Bang, the event in which the present expanding universe was created.

Since both the solar wind and the planetary ionosphere are dominated by hydrogen and helium, it is natural to conclude that Jupiter’s magnetosphere must also be mainly ionized hydrogen and helium atoms. That belief was never seriously questioned during the analysis of the Pioneer data.

Such was the state of affairs in early 1979, a few weeks before the Voyager 1 encounter with Jupiter, when I heard from L. J. Lanzerotti, a Voyager team member at AT&T Bell Laboratories. He told me that the Voyager ultraviolet spectrometer was finding abundant sulfur and oxygen ions in the Jovian magnetosphere, with no indication of hydrogen at all! My reaction was that this result was simply impossible to believe. Why sulfur and oxygen? It was clear that something crazy was going on, but we had no idea what it could be. As Voyager came closer to the planet, the APL instrument detected a few sulfur ions that had escaped from the magnetosphere. Even this direct sample of Jupiter’s plasma, however, was not enough to reveal what was going on inside.

The Voyager encounter greatly clarified the situation. Sulfur and oxygen ions are indeed the most abundant species by number in Jupiter’s magnetosphere. At thermal energies of about 50 electronvolts, they dominate both the mass and charge densities in the magnetosphere. Sulfur and oxygen ions continue to be important or dominant in the composition at energies up to several megaelectronvolts. These results are confirmed not only by Voyager ultraviolet spectroscopy but also by in-situ plasma and energetic particle measurements on Voyager. Subsequently, observations by ground-based optical spectrometers and the International Ultraviolet Explorer (an earth-orbiting satellite) have also confirmed the sulfur and oxygen composition of the magnetosphere. That composition is unique in the known universe.

Where do the sulfur and oxygen come from? The Voyager imaging experiment provided the key to the answer with the discovery of active volcanoes on Jupiter’s moon Io (Fig. 1). Io is slightly larger than Earth’s moon and is the only object in the solar system, other than Earth, known to have active volcanoes. Both on Earth and Io, volcanic eruptions are driven by the vapor pressure of erupting material. In terrestrial volcanoes, the driving gas is water (steam), but in Io’s volcanoes, the gas is sulfur dioxide (there may also be a contribution from sulfur). The Voyager infrared spectrometer detected gaseous sulfur dioxide near one of Io’s volcanic plumes. Ground-based infrared observations subsequently also discovered sulfur dioxide frost on Io’s surface.

Hence, it was immediately clear that Io, with its sulfur dioxide volcanoes and surface frost, was the ultimate source of the sulfur and oxygen in Jupiter’s magnetosphere. However, the volcanic eruptions themselves are

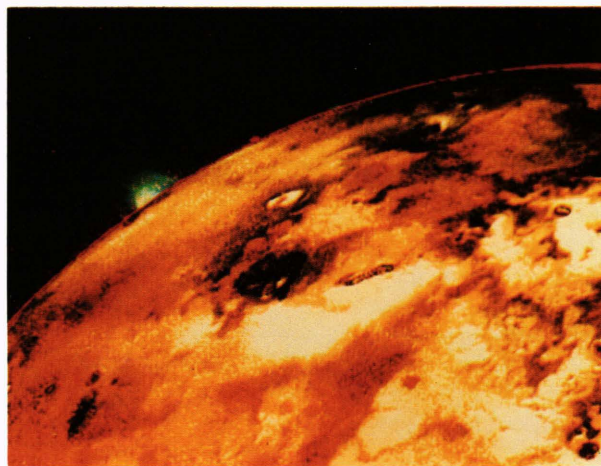


Figure 1—An active volcano seen at the limb of Jupiter’s moon Io. The volcanic plume rises to a height exceeding 100 kilometers.

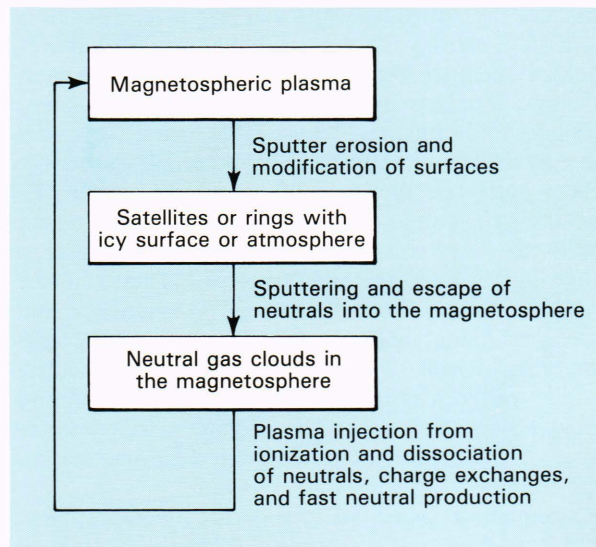


Figure 2—Interactions between a planetary magnetosphere and embedded satellites and rings.

not energetic enough to drive sulfur and oxygen into space against Io’s gravity, and the atmosphere is too cold for thermal escape to be adequate. How do sulfur and oxygen escape from Io?

It turns out that the magnetosphere itself is the agent that drives sulfur and oxygen from Io by a mechanism called sputtering.⁹ The magnetospheric plasma is also responsible for ionizing the sulfur and oxygen to create the very ion population that dominates its own composition. The surface and atmosphere of Io are therefore tightly coupled to the Jovian magnetosphere by a remarkable chain of processes, diagrammed in Fig. 2.

The first link in the chain is sputtering by magnetospheric ions. Sputtering is the process in which the impact of high-speed ions onto a solid target surface (or a gaseous atmosphere) causes ejection of atoms and molecules. Ejection of target species occurs by a variety

of mechanisms, including a cascade of elastic collisions resulting from penetration of the incident ion into the target and the excitation of target electrons to antibonding states (causing the ejection of target species). Chemical decomposition of the target can result. A schematic of sputtering and decomposition of methane ice is given in Fig. 3.

Magnetospheric ions will impact Io or its atmosphere at high speeds even if they do not have high random velocities (that is, they do not need high temperatures) because of plasma corotation. Jupiter's magnetic field rotates with the conducting core of the planet once every 9 hours, 55 minutes, and 29.7 seconds. A rotating magnetic field of arbitrarily asymmetric geometry will force a low-energy plasma to corotate with it if electrical contact is maintained with the rotating central conductor. The magnetic field lines are like rigid wires on which charged particles are forced to slide. In this way, Jupiter's magnetosphere is forced to corotate with the planet. At the location of Io, the corotation velocity alone of a sulfur ion corresponds to an energy of almost 520 electronvolts, while that of an oxygen ion is about 260 electronvolts. Both energies are adequate for highly efficient sputtering. Of course, much more energetic ions, with large gyration velocities around magnetic field lines and large parallel velocities, are also present and may make an important contribution to sputtering.

The sputter ejecta are mainly atoms and molecules containing sulfur and oxygen. The ejecta with sufficient velocity to escape Io's gravity are nevertheless unable to escape Jupiter's gravity, and their orbits around Jupiter are similar to Io's orbit. A cloud of neutral atoms and molecules in the shape of a torus (doughnut) forms around Io's orbit. These sulfur and oxygen neutral clouds have been observed by earth-based optical and ultraviolet spectrometers. The average atomic oxygen density in the neutral clouds is about 30 atoms per cubic centimeter.

Once neutral gas clouds form in the magnetosphere, rapid ionization and dissociation take place owing to electron impact and charge-exchange reactions. In a charge-exchange reaction, an incident ion strips one or more electrons from a target atom or molecule, causing ionization and/or dissociation. The incident ion can become electrically neutral as a result of the reaction; if it does, it becomes a high-speed neutral that escapes from the magnetosphere. Such high-speed neutrals from charge exchange reactions in Jupiter's magnetosphere, as well as charge exchange neutrals from Saturn and Earth,¹⁰ have been observed by particle detectors.

The rapid ionization and dissociation of the neutral clouds around Io's orbit cause rapid injection of sulfur and oxygen ions there, forming the Io plasma torus (see Fig. 4). Plasma injection into the Io torus is the dominant plasma source in the Jovian magnetosphere. The source of sulfur and oxygen ions is about 2×10^{28} ions per second, corresponding to a mass injection of 10^6 grams per second.

In addition to the atomic sulfur and oxygen clouds in the plasma torus, there is an atomic sodium cloud also thought to be maintained by sodium sputtering from Io.

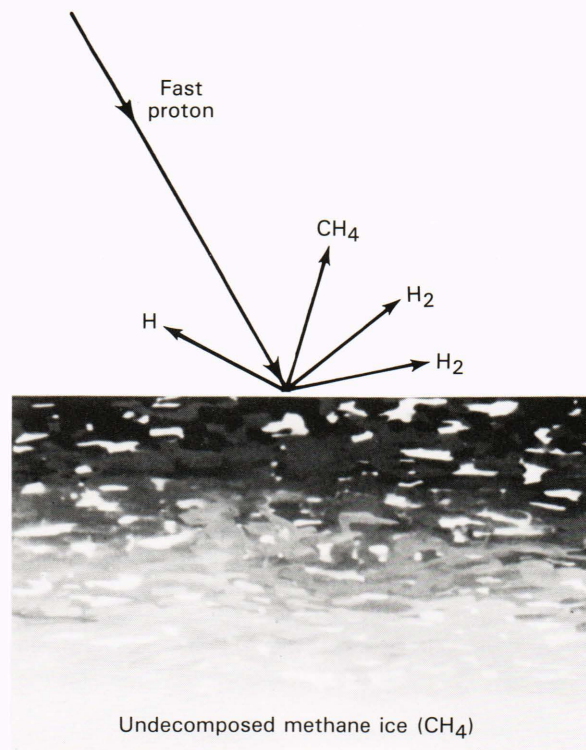


Figure 3—Sputtering and decomposition of methane ice under bombardment by energetic charged particles. There is ejection of atomic and molecular hydrogen as well as methane, forming a dark, carbon-enriched residue. In 100 years, 10 thousand trillion protons per square centimeter produce darkened organic residue on the surface.

This cloud was discovered by earth-based optical spectroscopy prior to the Voyager encounters. Injection of sodium ions into the plasma torus makes relatively minor contributions to the magnetospheric mass and energy budgets.

The Io plasma torus is an interesting and important astrophysical object in its own right. Its electron density (about 2000 per cubic centimeter) and its electron temperature (about 7 electronvolts in its hot portion) are very similar to those of the Orion nebula, the famous HII region that forms part of the Orion constellation. The Orion nebula gives many of the same oxygen and sulfur emission lines that are seen from the Io torus, although the Io torus does not give hydrogen emissions like those from Orion. The Io torus extends only from 5 to 7 Jupiter radii so it is much smaller than Orion and its emission lines are much less intense.

Figure 2 shows the chain of processes that links the Jovian magnetosphere (specifically the Io plasma torus), the surface and atmosphere of Io, and the neutral gas clouds. The chain is shown as being closed on itself, meaning that the Io plasma torus is self-regenerating. Each ion impact on Io's surface or atmosphere results in loss of the ion from the plasma torus. But many neutrals (tens to thousands) are sputtered into the neutral clouds, and a large fraction of them are eventually ionized and reinjected into the torus, resulting in a net

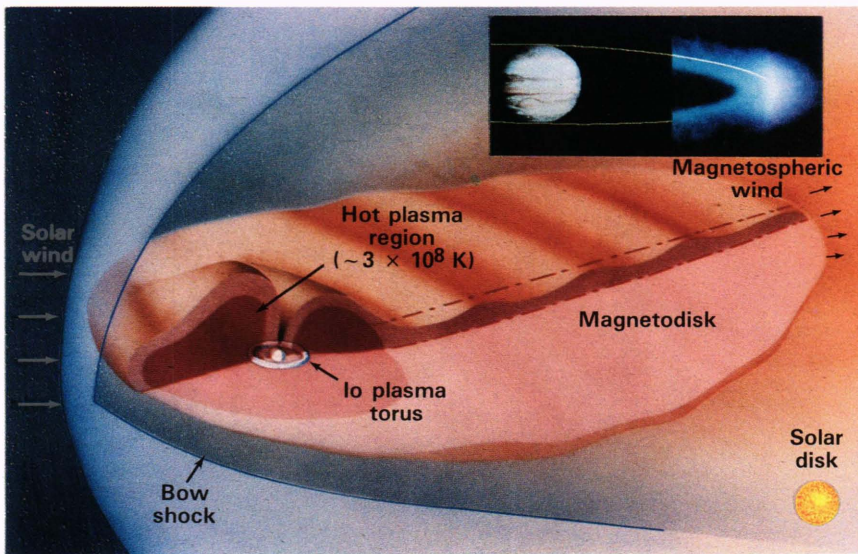


Figure 4—An overview sketch of Jupiter's magnetosphere showing the Io plasma torus. The size of the solar disk is shown for comparison. Inset: A ground-based spectrometer image of ionized sulfur emissions from the Io torus, with a superimposed photograph of Jupiter. (Adapted from Ref. 11.)

increase in the ion population of the torus. Indeed, the plasma torus would grow indefinitely except that it becomes unstable to interchanges. The interchange instability is analogous to the Rayleigh-Taylor instability in ordinary fluids that occurs when a dense fluid overlies a light one. The two fluids are unstable to overturning and exchanging places. If you turn a water glass upside down, instability allows water to run out even though atmospheric pressure is more than adequate to support the weight of the few inches of water. At Jupiter, the rapid plasma rotation causes centrifugal force to dominate gravity, and interchanges are centrifugally driven. The interchanges cause a rapid transport of plasma out from the torus, allowing sulfur and oxygen ions to fill the Jovian magnetosphere and limiting the growth of the Io torus.

This view of the Jupiter-Io system is appealing and self-consistent; it also seems to explain an apparently unrelated phenomenon—the Jovian ultraviolet aurora. The Voyager LECP experiment found that the fluxes and phase space densities of energetic ions (above several hundred kiloelectronvolts) decreased precipitously within the outer edge of the Io torus near 7 Jupiter radii (see Fig. 5). The losses of energetic ions are balanced by inward transport from the outer magnetosphere. The loss rate of energetic ions can be determined quantitatively from knowledge of the transport rate. However, the latter is driven by the same centrifugal interchanges that transport the thermal sulfur and oxygen plasma outward from the plasma torus. The transport is diffusive in both cases and is inward for the energetic ions but outward for the thermal plasma (since the direction of diffusive transport depends on the sign of the phase space density gradient, which is opposite in the two cases). The diffusion coefficient can be determined from the transport rate required to balance the thermal-plasma injection rate. The latter can be inferred from spectroscopic observations and from in-situ plasma measurements. The radial transport lifetime of ions in the torus turns out to be about 100 days. The corresponding diffusion

coefficient can be used to find the loss rate of energetic ions.

The results of such analyses (see Fig. 5) show that energetic ions are lost at a rate that may be high enough to explain the Jovian ultraviolet aurora.¹² The loss mechanism appears to be pitch-angle scattering by plasma waves, causing energetic ions to precipitate into Jupiter's upper atmosphere. There they create secondary electrons that excite ultraviolet auroral emissions. The total power input to the atmosphere may approach 10^{14} watts, compared to 10^{11} watts for Earth's aurora.

In summary, considerable progress has been made in understanding the escape of sulfur and oxygen from Io and the injection and transport of sulfur and oxygen ions into the magnetosphere. However, many unanswered questions remain. One is the relative proportion of sulfur to oxygen in the plasma torus. For technical reasons, this is not easily determined from Voyager data and ground-based data give conflicting results. Is sulfur dioxide volcanism the only volcanism on Io, or are there also sulfur volcanoes? Are there temporal variations in the density and composition of the plasma torus? How do the electrons in the plasma torus remain hot? Without a continual source of energy, the electrons would cool in a matter of hours, and the torus ultraviolet emissions that are driven by electron impact would cease. One possibility is that the electrons are kept hot by coulomb collisions with the much hotter ion plasma in the torus. Ions in the plasma torus are born hot because of a process called pickup. An atom in the neutral gas cloud orbits Jupiter at a speed much lower than corotation speed. Upon ionization, the new ion is picked up by the rotating magnetic field and acquires a gyration velocity around the field line equal to the difference between the corotation and the orbit speeds. The associated ion gyration energy is then available to heat the electrons. The ultimate energy source for this pickup process is, of course, the rotation of Jupiter. However, it is not clear if collisional energy transfer from ions suffices to maintain the electron temperature; additional energy sources

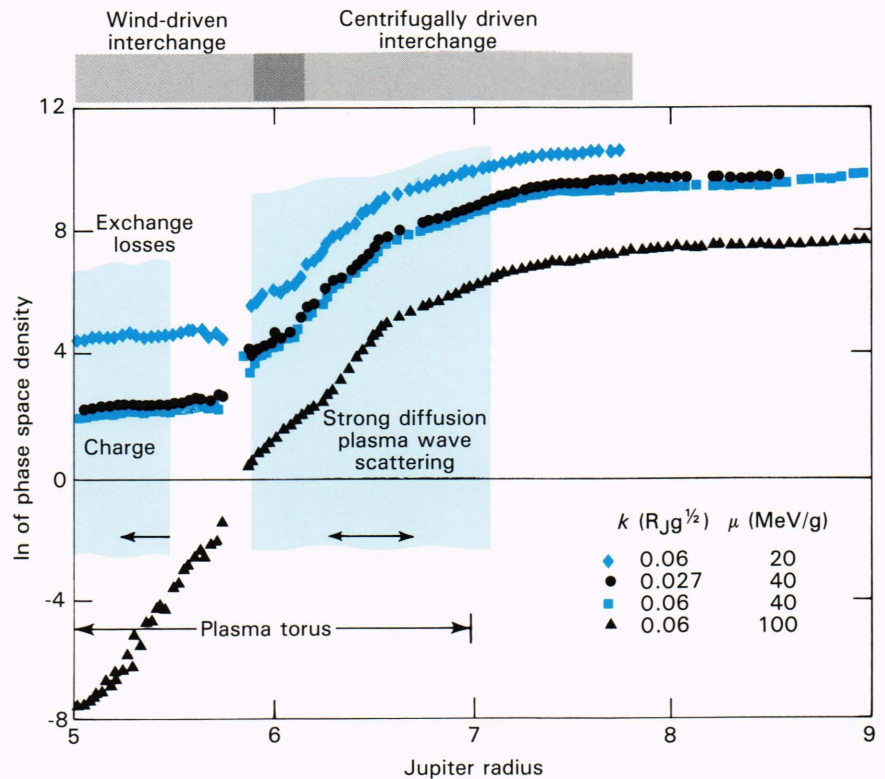


Figure 5—Plasma transport and energetic ion losses near the Io plasma torus. Phase space densities (arbitrary units) are plotted versus L , the equatorial crossing radius of a dipole field line in units of planetary radii, for various values of the first and second adiabatic invariants of charged particle motion, μ and K .

may be required. Secondary electrons from the precipitation of energetic ions may also be important.

There are many other unanswered questions concerning the magnetosphere of Jupiter: How are ions and electrons accelerated to very high energies? Electrons, for example, are observed at tens of megaelectronvolts of energy near the magnetopause. How are these energetic particles released into the interplanetary medium? At energies of less than several tens of megaelectronvolts, Jovian electrons apparently enter the inner heliosphere and can dominate the ambient population even near Earth. Are there global magnetospheric disturbances at Jupiter analogous to substorms at Earth?

SATURN

After the discoveries of volcanoes on Io, neutral gas clouds in the Jovian magnetosphere, and the Io plasma torus, it was widely anticipated that interactions between Saturn's magnetosphere and its major satellites and rings might be similarly important. Such is indeed the case, although there are major differences between the magnetospheres of Jupiter and Saturn that are not yet fully understood. In fact, Saturn's magnetosphere is generally less well understood than Jupiter's.

Unlike the situation at Jupiter, where the single moon Io dominates the satellite-magnetosphere interactions, several moons have important magnetospheric interactions at Saturn (see Fig. 6), including Mimas, Enceladus, Tethys, Dione, and Rhea. All are icy moons with radii up to about half that of Earth's moon, and all have substantial fractions of their surfaces covered by water ice. These icy moons are all located in the inner magneto-

sphere within 3 to 9 Saturn radii. In addition, Saturn's moon Titan interacts strongly with the outer magnetosphere. Titan is larger than Mercury and has a dense atmosphere consisting mainly of nitrogen and methane plus other hydrocarbons. It is far enough from Saturn (20.2 Saturn radii) that it occasionally finds itself outside Saturn's magnetosphere as the magnetospheric boundaries move in and out (partly in response to changes in the dynamic pressure of the solar wind). Titan was within the magnetosphere during the Voyager 1 encounter (and perhaps part of the Voyager 2 encounter).

The interaction of the icy moons with the magnetosphere can be summarized by Fig. 3. Charged particle sputtering and sputtering of icy surfaces on the moon by ultraviolet photons cause ejection of water and lesser quantities of various dissociation fragments into the magnetosphere, forming vast neutral gas clouds. The clouds are ionized and dissociated to maintain an oxygen-heavy plasma torus that was observed both by Pioneer and by the Voyager spacecraft. The ion densities show a broad peak between the orbits of Tethys (4.9 Saturn radii) and Dione (6.3 Saturn radii), and the maximum density is about 50 ions per cubic centimeter. Electron temperatures there are variable and range from less than 10 to more than 100 electronvolts. However, the Voyager instruments were unable to identify which heavy ions are the most important constituents. The presence of a neutral gas cloud in the inner magnetosphere has been inferred from Voyager LECP observations of charge-exchange neutrals from Saturn¹⁰ that suggest a neutral cloud containing water and dissociation products extending from 3 to 11 Saturn radii, with a total

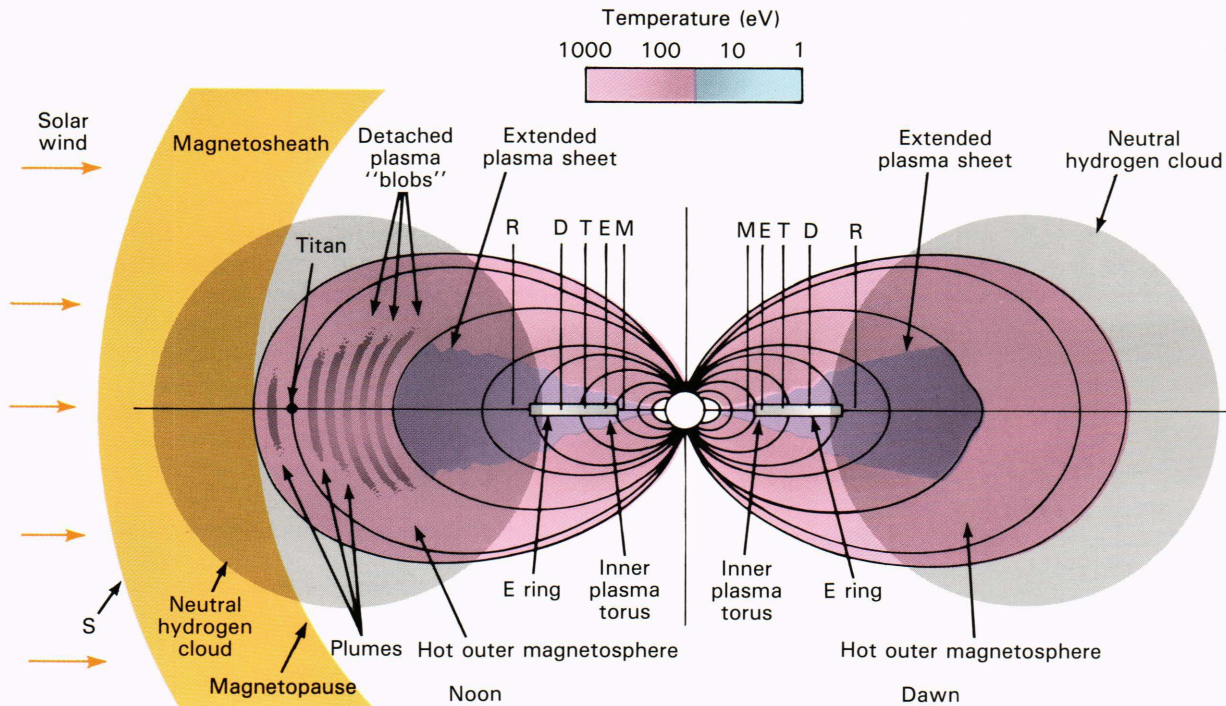


Figure 6—An overview sketch of Saturn's magnetosphere and embedded moons Titan, Rhea (R), Dione (D), Tethys (T), Enceladus (E), and Mimas (M). Two cross sections of the magnetosphere are drawn at noon and dawn local times in the left and right halves of the figure.

thickness of 1.5 Saturn radii and an average density of 20 per cubic centimeter. No other emissions have been observed from this neutral cloud, either from space or from the ground, at wavelengths from the infrared to the ultraviolet. Likewise, no optical or ultraviolet emissions from ions in the plasma torus have been observed.

The lack of independent information from optical and ultraviolet spectroscopy of Saturn's water cloud and inner plasma torus has greatly hindered our understanding of those objects. In contrast with the situation at Jupiter, the importance of interactions between Saturn's magnetosphere and its icy moons for the magnetospheric mass and energy budgets is not yet clear.

The interaction between Titan and Saturn's magnetosphere resembles that of Venus with the solar wind. Titan, like Venus, does not have a strong intrinsic magnetic field, so the corotating plasma of Saturn's magnetosphere impacts directly on Titan's dense, collisional atmosphere. A long tail of protons and heavy ions (mainly nitrogen ions) is extracted and carried downstream, analogous to the ion tail of comets; the resulting loss rate of heavy ions from Titan is about 10^{24} per second. In addition, about 3×10^{27} hydrogen atoms and molecules and about 3×10^{26} nitrogen atoms escape from Titan each second.

These neutrals (hydrogen atoms and molecules and nitrogen atoms) escape into the magnetosphere and form the Titan torus, a vast neutral gas cloud orbiting Saturn. The existence of an atomic hydrogen torus around Saturn supplied by Titan was actually predicted well before the Pioneer and Voyager encounters.¹³ The Voy-

ager ultraviolet spectrometer observed that the atomic hydrogen cloud of the Titan torus extended radially from 8 to 25 Saturn radii with an average density of 10 to 20 per cubic centimeter. Ionization of neutrals in the Titan torus is clearly an important plasma source for the magnetosphere, but may not be dominant. The Titan torus also differs from the Io torus in that the escape of neutrals from Titan is not driven primarily by the impact of magnetospheric ions. Indeed, Titan may not even be the dominant source of neutrals for the Titan torus; Saturn's upper atmosphere may also be an important source of atomic hydrogen.

Saturn's magnetosphere interacts strongly with the rings and the moons. Of particular interest here is the E ring that extends from 3 to 8 Saturn radii, with peak density near the orbit of Enceladus at 4 Saturn radii. The E ring therefore lies within the inner heavy ion plasma torus. It is detectable by ground-based telescopes but only when the rings are edge-on to Earth. It consists of micrometer-sized grains, probably water ice, but its total surface is small compared to that of the moons. Sputtering of the E ring is therefore not an important source for the water cloud in the inner magnetosphere.

The difficulty in understanding the E ring is that it should be destroyed rapidly by interaction with the magnetosphere. The lifetime of its grains against sputtering erosion and outward radial transport (from interaction with the plasma) may be as short as 100 years. Will the E ring shortly disappear, or is it continually replenished? Can Enceladus be the source of E ring grains? There are no geysers on Enceladus, but there may have been

a catastrophic impact in the recent past. Alternatively, can the E ring be maintained by vapor deposition from the neutral cloud?

There are many other unresolved questions about Saturn's magnetosphere. What is the identity of the heavy ions in the inner and outer magnetospheres? Is it oxygen in the former case and nitrogen in the latter? Another problem is that Saturn's ultraviolet aurora is not related to the heavy ion plasma torus in the inner magnetosphere, since the aurora does not occur on the same magnetic field lines. This contrasts with the situation at Jupiter, where the ultraviolet aurora is magnetically connected to the Io plasma torus. Does Saturn have an Earth-like aurora? Does Saturn have substorms?

URANUS

Voyager 2 discovered a magnetosphere at Uranus in January, 1986. Analysis of the encounter data has barely begun. Preliminary reports have been published in *Science*,¹⁴ but it is clearly premature to attempt a survey of satellite-magnetosphere interactions at Uranus.

Uranus has five icy moons within its magnetosphere: Miranda, Ariel, Umbriel, Titania, and Oberon (see Fig. 7). They are comparable in diameter to Saturn's icy moons and have a substantial portion of their surfaces covered by water ice, like the icy moons of Saturn and Jupiter. However, the icy moons of Uranus are generally darker than those of Saturn, and they have some dark, spectrally bland material on their surfaces that probably contains carbon. The rings of Uranus are also very dark with albedoes of about 5 percent.

We pointed out prior to the Voyager 2 encounter that the presence of black material on the icy moons and in the rings of Uranus could be explained by energetic particle bombardment of carbon-bearing ices (such as methane).¹⁵ Laboratory experiments have shown that particle irradiation of carbon-bearing ices produces a black, carbon-enriched, polymerized residue (see Fig. 3). We then

predicted that Uranus would have a magnetosphere and intense particle radiation belts. The Voyager encounter¹³ verified that, indeed, the energetic particle fluxes at Uranus are sufficient to blacken and polymerize exposed methane ice surfaces within 10^4 to 10^5 years.

However, the magnetosphere of Uranus did surprise us in many ways. One major surprise is the large angle, 60 degrees, between the magnetic and rotation axes. This angle is far larger than that observed at any other planet and has major consequences for the magnetospheric configuration (see Fig. 7) that have not yet been fully explored. The magnetic axis of Uranus is not currently aligned with the solar wind flow, as was supposed prior to encounter. Another surprise is that, so far, only protons (and a very small abundance of neutral or ionized molecular hydrogen) have been detected in the magnetosphere. Where are the heavy ions? Oxygen ions, in particular, should be injected into the magnetosphere following ionization and dissociation of sputtered water. Needless to say, more work is needed. Another surprise is that Voyager energetic particle data in the radiation belts¹⁴ showed strong signatures of satellite sweeping-absorption of energetic particles by the icy moons. If an energetic particle strikes a moon, it is simply absorbed and lost from the radiation belt. Neutrals are sputtered and eventually ionized, but the new ions must be accelerated considerably before attaining radiation-belt energies (about 100,000 electronvolts). Satellite sweeping occurs at Jupiter and Saturn, but its effects are much less prominent there, perhaps because of competing loss processes at Jupiter and Saturn such as interaction with plasma waves. Finally, ultraviolet aurorae were observed on the nightside and the dayside of Uranus, and a bright ultraviolet emission called "electroglow" was observed on the dayside.¹⁶ The interpretation of these emissions is not clear at present.

SUMMARY

We have seen that the magnetospheres of the outer planets interact strongly with the surfaces and atmospheres of planetary satellites and rings. At Jupiter, Saturn, and Uranus the processes of charged-particle sputtering, formation of neutral gas clouds, and rapid plasma injection from ionization of the neutral clouds have important implications for the magnetosphere as a whole and for the surfaces and atmospheres of the satellites. We have learned a great deal by comparing the magnetospheres of the outer planets and identifying common physical processes, as well as by trying to understand the differences that we observe. Ultimately, we can expect to understand and predict better the behavior of the magnetosphere of our own planet Earth. Onward to Neptune!

REFERENCES and NOTES

- 1 T. Gehrels, ed., *Jupiter*, University of Arizona Press, Tucson (1976).
- 2 A. J. Dessler, ed., *Physics of the Jovian Magnetosphere*, Cambridge University Press, New York (1983).
- 3 T. Gehrels and M. Mathews, eds., *Saturn*, University of Arizona Press, Tucson (1984).

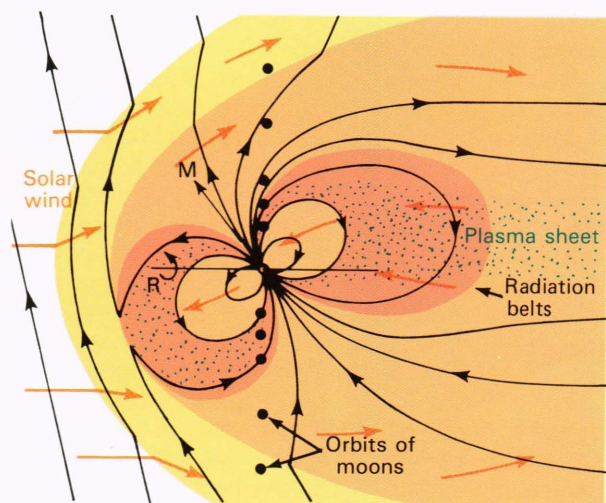


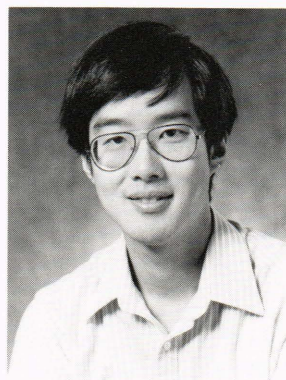
Figure 7—An overview sketch of the Uranian magnetosphere showing radiation belts and satellites. There is a large 60 degree angle between the magnetic axis (M) and the rotation axis (R, marked by the arrow).

- ⁴A. F. Cheng, P. Haff, R. E. Johnson, and L. Lanzerotti, "Interaction of Planetary Magnetospheres with Io Satellite Surfaces," in *Satellites*, J. A. Burns and D. Morrison, eds., University of Arizona Press, Tucson (1986).
- ⁵J. F. Carbary and S. M. Krimigis, "Encounters with Jupiter: The Low Energy Charged Particle Results of Voyager," *Johns Hopkins APL Tech. Dig.* **1**, 60-63 (1980).
- ⁶J. F. Carbary and S. M. Krimigis, "Low Energy Charged Particles at Saturn," *Johns Hopkins APL Tech. Dig.* **2**, 87-89 (1981).
- ⁷S. M. Krimigis, "A Post-Voyager View of Saturn's Environment," *Johns Hopkins APL Tech. Dig.* **3**, 180-188 (1982).
- ⁸D. Venkatesan, "Cosmic-Ray Picture of the Heliosphere," *Johns Hopkins APL Tech. Dig.* **6**, 4-19 (1985).
- ⁹A. F. Cheng, "Escape of Sulfur and Oxygen from Io," *J. Geophys. Res.* **89**, 3939 (1984) and references therein.
- ¹⁰A. F. Cheng, "Energetic Neutral Particles from Jupiter and Saturn," *J. Geophys. Res.* **91**, 4524 (1986). See also discovery papers, E. Kirsch, S. M. Krimigis, J. Kohl, and E. Keath, "Upper Limits for X-Ray and Energetic Neutral Particle Emission from Jupiter: Voyager 1 Results," *Geophys. Res. Lett.* **8**, 169 (1981) and E. Kirsch, S. M. Krimigis, W. Ip, and G. Gloeckler, "X-Ray and Energetic Neutral Particle Emission from Saturn's Magnetosphere," *Nature* **29**, 718 (1981) for original observations at Jupiter and Saturn. E. Roelof et al., "Energetic Neutral Atoms ($E \sim 50$ keV) from the Ring Current: IMP 7/8 and ISEE-1," *J. Geophys. Res.* **90**, 10991-11008 (1985) discuss observations at Earth.
- ¹¹*An Implementation Plan for Priorities in Solar System Space Physics*, Committee on Solar and Space Physics of the Space Science Board, National Research Council, National Academy Press, Washington, D.C. (1985).
- ¹²A. F. Cheng, "Radial Diffusion and Ion Partitioning in the Io Torus," *Geophys. Res. Lett.* **13**, 517 (1986) and A. F. Cheng, C. MacLennan, L. Lanzerotti, M. Paonessa, and T. Armstrong, "Energetic Ion Losses Near Io's Orbit," *J. Geophys. Res.* **88**, 3936 (1983) and references therein.
- ¹³T. McDonough and N. Brice, "New Kind of Ring Around Saturn," *Icarus* **20**, 136 (1973).
- ¹⁴S. M. Krimigis, T. Armstrong, W. Axford, A. Cheng, G. Gloeckler, D. Hamilton, E. Keath, L. Lanzerotti, and B. Mauk, "The Magnetosphere of Uranus: Hot Plasma and Radiation Environment," *Science* **233**, 97 (1986). Also see reports of other Voyager investigations in the same special issue of *Science*.
- ¹⁵A. F. Cheng, "Magnetosphere, Rings, and Moons of Uranus," in *Uranus and Neptune*, J. Bergstrahl, ed., NASA CP-2330, p. 541 (1984); A. F. Cheng and L. J. Lanzerotti, "Ice Sputtering by Radiation Belt Protons and the Rings of Saturn and Uranus," *J. Geophys. Res.* **83**, 2597 (1978).

- ¹⁶A. L. Broadfoot et al., "Ultraviolet Spectrometer Observations of Uranus," *Science* **233**, 74 (1986) report on Voyager observations. IUE observations are reported by J. T. Clarke, "Detection of Auroral H Ly α Emission from Uranus," *Astrophys. J.* **263**, L105 (1982) and by S. T. Durrance and H. W. Moos, "Intense Ly α Emission from Uranus," *Nature* **299**, 428 (1982).

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