Annu. Rev. Earth Planet. Sci. 1992. 20:289–328

GIANT PLANET MAGNETOSPHERES

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KEY WORDS: Jupiter, Saturn, Uranus, Neptune

INTRODUCTION

As its name suggests, a planet's magnetosphere is the region of space influenced by the planet's magnetic field. The Voyager tour of the outer solar system has confirmed that, like Earth, all four giant planets have extensive magnetospheres due to their strong magnetic fields, generated by convective motions in an electrically-conducting region in the planet's interior. The magnetospheres of Jupiter, Saturn, Uranus, and Neptune vary in size, form, and content but share common features: They are all large structures dominated by strong planetary magnetic fields that contain thermal plasma; there are processes that accelerate the thermal plasma to produce populations of energetic particles which are trapped in radiation belts around the planets; there are significant interactions between the plasma and satellites that are embedded in the magnetospheres; and each magnetosphere produces similar types of plasma waves, radio emissions, and aurora. With the Voyager spacecraft having made measurements with the same complement of instruments at the four planets we can now make a comparison of the family of magnetospheres. The topic of planetary magnetospheres has been reviewed previously by Siscoe & Slavin (1979), Stern & Ness (1982), Bagenal (1985a), Connerney (1987), Hill & Dessler (1991), and McNutt (1991).

The orientations of the planet and its magnetic field control the morphology and dynamics of a planet's magnetosphere. We first consider how the giant planet magnetospheres fall into two categories—the large, symmetric magnetospheres of Jupiter and Saturn and the smaller, irregular

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magnetospheres of Uranus and Neptune. We then discuss the characteristics of the plasma and our current understanding of the magnetospheric processes for each planet in turn. Finally, we compare the energetic particle populations, radio emissions, and remote sensing of magnetospheric processes in these giant planet magnetospheres.

PLANETARY MAGNETIC FIELDS

Table 1 shows a comparison of planetary magnetic fields. While the net magnetic moment of each of the outer planets is many times greater than that of the Earth, the planets' large radii result in magnetic fields at the surface (or cloud tops) that are all on the order of a Gauss. None of the planetary magnetic fields are purely dipolar but the dipole (first order) approximation gives an indication of the strength (B_0) and orientation of the field. The regularity of the planet's magnetic field can be gauged by the tilt of the dipole axis from the rotation axis and by deviation of the minimum and maximum surface field strengths from B_0 and $2B_0$

Table 1 Comparison of planetary magnetic fields

	Earth	Jupiter[a]	Saturn[a]	Uranus[a]	Neptune[a]
Radius, R_{Planet} (km)	6,373	71,398	60,330	25,559	24,764
Spin Period (Hours)	24	9.9	10.7	17.2	16.1
Magnetic Moment /M_{Earth}	1[b]	20,000	600	50	25
Surface Magnetic Field (Gauss)					
Dipole Equator, B_0	0.31	4.28	0.22	0.23	0.14
Minimum	0.24	3.2	0.18	0.08	0.1
Maximum	0.68	14.3	0.84	0.96	0.9
Dipole Tilt and Sense[c]	+11.3°	-9.6°	-0.0°	-59°	-47°
Distance (A.U.)	1[d]	5.2	9.5	19	30
Solar Wind Density (cm^{-3})	10	0.4	0.1	0.03	0.005
R_{CF}	8 R_E	30 R_J	14 R_S	18 R_U	18 R_N
Size of Magnetosphere	11R_E	50-100 R_J	16-22 R_S	18 R_U	23-26 R_N

[a] Magnetic field characteristics from Acuña & Ness (1976), Connerney et al (1982, 1987, 1991).
[b] $M_{Earth} = 7.906 \times 10^{25}$ Gauss $cm^3 = 7.906 \times 10^{15}$ Tesla m^3.
[c] Note: Earth has a magnetic field of opposite polarity to those of the giant planets.
[d] 1 A.U. $= 1.5 \times 19^8$ km.

respectively. Jupiter and Saturn have magnetic fields like that of the Earth, where the magnetic axis is roughly aligned with the rotation axis and has only moderate deviation from a dipole. Uranus and Neptune on the other hand, have very irregular magnetic fields with magnetic axes at large angles from their rotation axes and large deviations from a dipole field.

The details of a planet's magnetic field are determined by fitting magnetometer data obtained along spacecraft trajectories with a spherical harmonic expansion model of the magnetic field (e.g. Connerney 1981). Low-orbit satellites allow the Earth's magnetic field to be modeled to high order (Langel & Estes 1985). For the outer planets, spacecraft flybys provide only the lower-order terms (Connerney 1981; Connerney et al 1987, 1991). When the Earth's field is scaled to the core-mantle boundary (believed to be the outer boundary of the geodynamo), the spectrum is very flat, i.e. there is the same amount of power at all spatial scales (e.g. Langel & Estes 1982). This implies that the convective motions which drive the dynamo are small in scale. Connerney et al (1991) point out that should there be a similarly-flat spectrum at the boundary of dynamo regions of other planets, then the observed harmonic structure of Jupiter's and Saturn's fields imply that the outer boundaries of their dynamos are at 0.8 R_J and 0.4 R_S respectively. This is consistent with the expected locations of the pressure-induced transition from molecular (low conductivity) to metallic (high conductivity) hydrogen in each planet.

Following this line of argument, Connerney et al (1991) find that the large nondipolar components of the magnetic fields of Uranus and Neptune imply the existence of a flat spectrum very close to the planet's surface—an unlikely location of the dynamo region. Connerney et al (1991) argue that it is perhaps more realistic to attribute the nondipolar and highly inclined fields of Uranus and Neptune to a fundamental difference in their dynamo mechanisms. Discovery of the irregular field of Uranus, tempted some to ascribe the irregularity to our chancing upon Uranus during a reversal of the magnetic field, similar to the reversals found in the Earth's geologic record (Schultz & Paulikas 1990, Rädler & Ness 1990). The discovery of a second irregular field at Neptune, however, makes this idea implausible. Connerney et al (1991) took Parker's (1969) suggestion that a large tilt implies large convective cells and argue that for Uranus and Neptune large cells would be consistent with the lower conductivity of the liquid mantle region of these planets, which is thought to comprise water, ammonia, and methane.

In conclusion, there appear to be two different types of planetary dynamos. The planets with highly-conducting dynamo regions—Earth (iron), Jupiter, and Saturn (both metallic hydrogen)—have dynamos with small length scales which produce largely dipolar magnetic fields with small tilts with respect to the rotation axis. Stevenson (1982) further argues that in the particularly symmetric case of Saturn, the nonaxisymmetric components are attenuated by differential rotation of an outer conductive shell. Dynamos in planets with poorly-conducting mantles, such as Uranus and Neptune, operate over larger scales and generate nondipolar magnetic fields that are highly inclined to the planet's rotation axis. Perhaps planetary magnetic fields (the external manifestation of interior processes) could provide information about physical conditions inside planets, but we are currently hampered by our limited understanding of magnetic dynamos. Furthermore, we are unfortunately running out of planets on which to test dynamo theories.

MAGNETOSPHERIC MORPHOLOGY

The term *magnetosphere* was coined by Gold (1959) to describe the region of space wherein the principal forces on a plasma are electrodynamic in nature and are a result of the planet's magnetic field. Planetary magnetospheres are embedded in the solar wind, which is the outward expansion of the solar corona [see papers in Pizzo et al (1988) for reviews of the solar wind]. At Earth's orbit and beyond, the solar wind has an average speed of about 400 km s^{-1}. The density of particles (mainly electrons and protons) is observed to decrease, from values of about 3–10 cm^{-3} at the Earth, as the inverse square of the distance from the Sun, consistent with a steady radial expansion of the solar gas into a spherical volume. The solar wind speed, while varying between about 300 and 700 km s^{-1}, always greatly exceeds the speed of waves characteristic of a low density, magnetized, and completely ionized gas (Alfvén waves). Thus a shock is formed upstream of an obstacle, such as a planetary magnetosphere that is imposed on the super-Alfvénic solar wind flow. A planetary *bow shock* can be described in fluid terms as a discontinuity in bulk parameters of the solar wind plasma in which mass, momentum, and energy are conserved. Entropy, however, increases as the flow traverses the shock with the solar wind plasma being decelerated and heated so that the flow can be deflected around the magnetosphere. Thus a shock requires dissipative processes and the presence of a magnetic field allows dissipation to occur on a scale much smaller than a collisional scale length. Although planetary bow shocks do not play a significant role in magnetospheric processes, the crossings of spacecraft through planetary bow shocks have provided an opportunity to study the exotic plasma physics of high Mach number collisionless shocks that cannot be produced in a laboratory [for reviews of collisionless shocks see Stone & Tsurutani (1985); for discussion of giant planet bow shocks also see Russell et al (1982), Slavin et al (1985), Bagenal et al (1987), Moses et al (1990)].

To first approximation, the magnetic field of a planet deflects the plasma flow around it, carving out a cavity in the solar wind (Figure 1). The layer of deflected solar wind behind the bow shock is called the *magnetosheath* and the boundary between the magnetosphere and the solar wind plasma is called the *magnetopause*. The solar wind generally pulls out part of the planetary magnetic field into a long cylindrical *magnetotail*, extending far downstream behind the planet.

Well before Biermann (1957) provided cometary evidence of a persistent solar wind, Chapman & Ferraro (1931) considered how a strongly magnetized body would deflect a flow of particles from the Sun and made an estimate of the location of the magnetopause stagnation point—the boundary between the magnetosphere and the solar wind in the direction of the Sun. They proposed that a dipolar magnetic field (of strength B_0 at the planet's equatorial radius R_p) would stand off the flow to a distance R_{CF} where the external ram pressure of the solar wind balances the internal pressure of the planet's magnetic field: $R_{CF}/R_p = (B_0^2/8\pi m_i n_{sw} V_{sw}^2)^{1/6}$ (where m_i, n_{sw}, and V_{sw} are the ion mass, density, and flow speed of the solar wind). This approximation not only assumes that the magnetic pressure of the solar magnetic field that is embedded in the solar wind is negligible but also that the particle pressure inside the magnetosphere is small. Furthermore, the physical processes that may operate at the mag-

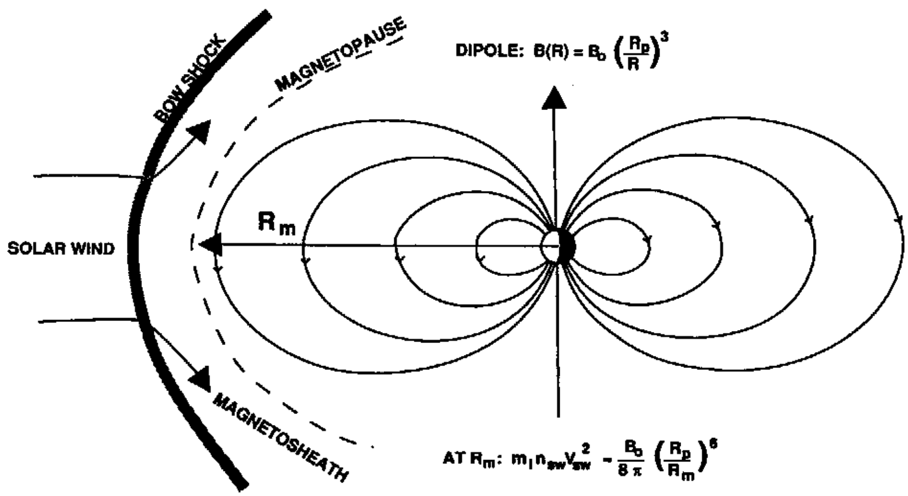


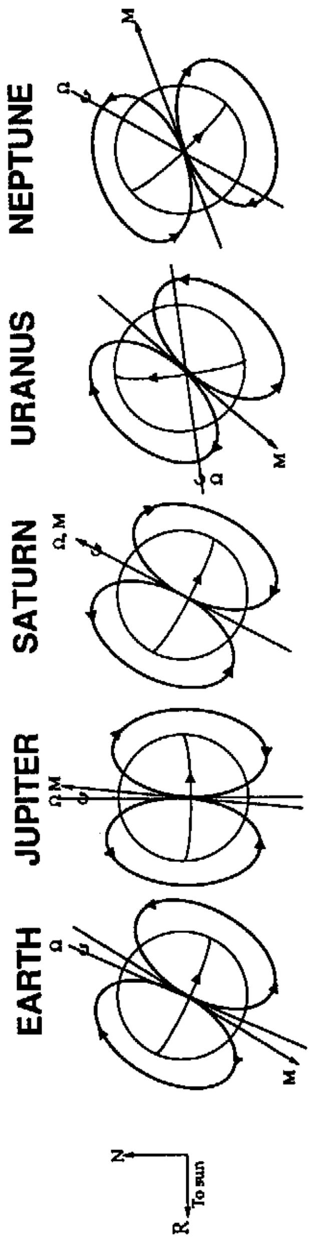
Figure 1 The Chapman-Ferraro solar wind stand-off distance for a dipole magnetic field.

netosphere boundary, such as electric currents resulting from the interconnection of the solar and planetary magnetic fields, are ignored. In reality, the observed magnetopause stand-off distance, R_m, is found to be a factor of 1–2 larger than R_{CF} (see Table 1). Jupiter is the only notable exception, where the plasma pressure inside the magnetosphere is sufficient to further "inflate" the magnetosphere. This makes the magnetosphere of Jupiter a huge object—about 1000 times the volume of the Sun with a tail that extends at least 6 AU in the antisunward direction, beyond the orbit of Saturn. If the Jovian magnetosphere were visible, from Earth its angular size would be twice that of the Sun even though it is at least four times farther away. The magnetospheres of the other giant planets are much more modest (while still dwarfing that of the Earth), having a similar scale of about 20 times the planetary radius—comparable to the size of the Sun.

While the size of a planetary magnetosphere depends on the strength of a planet's magnetic field, the configuration and internal dynamics depend on the field orientation (illustrated in Figure 2) which is described by two angles: the tilt of the magnetic field with respect to the planet's spin axis and the angle between the planet's spin axis and the solar wind direction which is generally within a few degrees of radially outward from the Sun. Since the direction of the spin axis with respect to the solar wind direction only varies over a planetary year (many Earth years for the outer planets) and the planet's magnetic field is assumed to vary only on geological time scales, these two angles are constant for the purposes of describing the magnetospheric configuration at a particular epoch. Earth, Jupiter, and Saturn have both small dipole tilts and small obliquities. This means that the orientation of the magnetic field with respect to the solar wind does not vary appreciably over a planetary rotation period and that seasonal effects are small. Thus Earth, Jupiter, and Saturn have symmetric and quasi-stationary magnetospheres, with Earth and Jupiter each exhibiting only a small wobble due to their $\sim 10^\circ$ dipole tilts. In contrast, the large dipole tilt angles of Uranus and Neptune mean that the orientation of their magnetic fields with respect to the interplanetary medium varies considerably over a planetary rotation period, thus making highly asymmetric and time-variable magnetospheres. Furthermore, Uranus' large obliquity means that the configuration of its magnetosphere will have strong seasonal changes over its 84-year orbit. Below we compare the morphologies of these two topologically-distinct types of magnetospheres.

Symmetric Magnetospheres

Magnetospheric configuration is generally well-described by magnetohydrodynamics (MHD) in which the magnetic field can be considered to be frozen into the plasma flow. Thus we need to consider the processes



	EARTH	JUPITER	SATURN	URANUS	NEPTUNE
Obliquity Cos^{-1} (Ω·N) =	23.5°	3.1°	26.7°	97.9°	29.6°
Dipole Tilt Cos^{-1} (Ω·M) =	+11.7°	-9.6°	-0.0°	-59°	-47°
Solar Wind Angle Cos^{-1}(Ω • R) =	66.5 - 113.5°	86.9 - 93.1°	63.7 - 116.5°	7.9 - 172.1°	60.4 - 119.6°

Figure 2 Orientations of the planets and their magnetic fields.

controlling magnetospheric flows [for further discussion of this topic see Vasyliunas (1983)]. The two largest sources of momentum in planetary magnetospheres are the planet's rotation and the solar wind. The nature of any large-scale circulation of material in the magnetosphere depends on which momentum source is tapped. For planetary magnetospheres, corotation of plasma with the planet is a useful first approximation with any departures from strict corotation occurring when certain conditions break down. It may be helpful to think of plasma in the magnetosphere as mass that is coupled by means of magnetic field lines to a giant flywheel (the planet) with the ionosphere acting as the clutch.

For magnetospheric plasma to rotate with the planet, the upper region of the neutral atmosphere must corotate with the planet and must be closely coupled to the ionosphere by collisions. The electrical conductivity of the ionosphere σ^{i} is large so that in a corotating ionosphere (with velocity $\mathbf{V}^{\mathrm{i}}$) any horizontal currents (perpendicular to the local magnetic field) are given by Ohm's law, $\mathbf{J}^{\mathrm{i}}_{\perp} = \sigma^{\mathrm{i}}_{\perp}(\mathbf{E}^{\mathrm{i}}+\mathbf{V}^{\mathrm{i}} \times \mathbf{B})$. Just above the ionosphere the conductivity perpendicular to the magnetic field in the (collision-free) magnetosphere, $\sigma^{\mathrm{m}}_{\perp}$, is essentially zero and $\mathbf{E}^{\mathrm{m}} = -\mathbf{V}^{\mathrm{m}} \times \mathbf{B}$. Because the plasma particles are far more mobile in the direction of the local magnetic field, the parallel conductivity $\sigma^{\mathrm{m}}_{\parallel}$ is large and the field lines can be considered to be equipotentials ($\mathbf{E} \cdot \mathbf{B} = 0$). Thus the electric field in the magnetosphere can be mapped into the ionosphere (Figure 3*a*). Because the ionosphere is relatively thin, the electric field $\mathbf{E}^{\mathrm{m}}$ just above the ionosphere is the same as $\mathbf{E}^{\mathrm{i}}$ so that we can write $\mathbf{J}^{\mathrm{i}}_{\perp} = \sigma^{\mathrm{i}}_{\perp}(\mathbf{V}^{\mathrm{i}}-\mathbf{V}^{\mathrm{m}}) \times \mathbf{B}$. The condition for corotation of the magnetospheric plasma is that the ratio $J^{\mathrm{i}}/\sigma^{\mathrm{i}}$ be sufficiently small so that $\mathbf{V}^{\mathrm{m}} = \mathbf{V}^{\mathrm{i}} = \mathbf{\Omega} \times \mathbf{r}$. For a dipolar magnetic field that is aligned with the rotation axis, the corotational electric field (in the equatorial plane) is therefore radial with magnitude $E_{\mathrm{co}} = \Omega B_0/r^2$.

It is clear that large ionospheric conductivities facilitate corotation. The large $\sigma^{\mathrm{m}}_{\parallel}$ also means that any currents in the magnetosphere that result from mechanical stresses on the plasma are directly coupled by field-aligned currents to the ionosphere. Thus corotation breaks down when mechanical stresses on the magnetospheric plasma drive ionospheric currents that are sufficiently large for the ratio $J^{\mathrm{i}}/\sigma^{\mathrm{i}}$ to become significant. Such conditions might occur in regions of the magnetosphere where there are large increases in mass density due to local ionization of neutral material, where there are strong radial motions of the plasma, or where there are sharp gradients in plasma pressure (Hill 1979). When the magnetosphere imposes too large a load, the ionospheric clutch begins to slip.

Next let us consider how the momentum of the solar wind may be harnessed by processes occurring near the magnetopause where the external solar magnetic field interconnects with the planetary magnetic field.

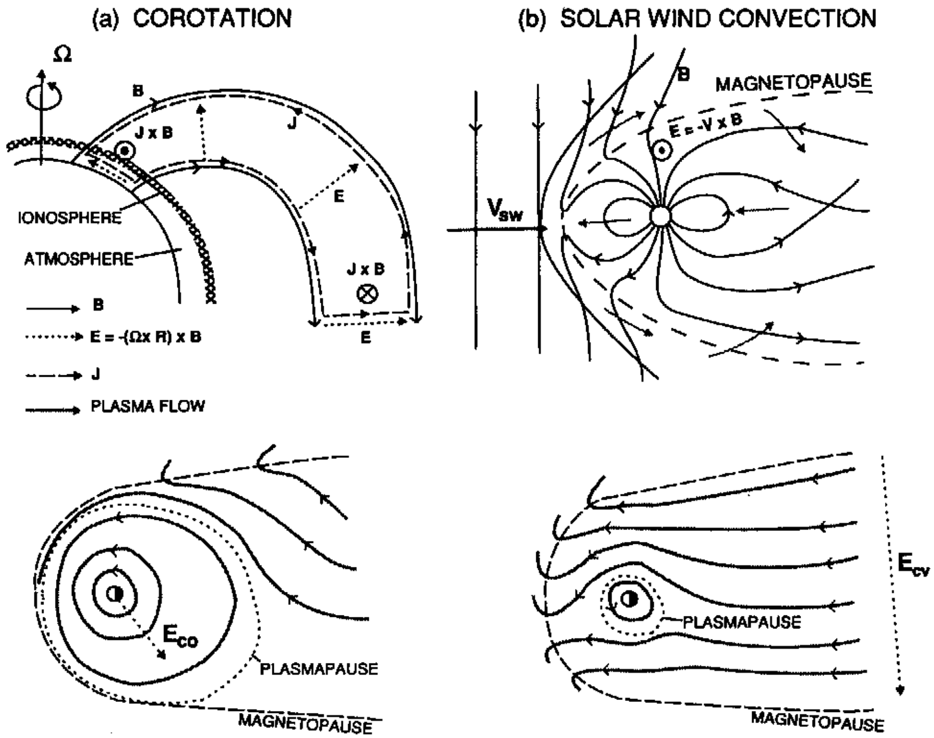


Figure 3 Large scale magnetospheric circulation driven by (*left*) corotation and (*right*) the solar wind. In each case, the upper (*lower*) diagram shows the meridianal view (the view in the equatorial plane). Magnetic field lines are continuous dark arrows; the directions of plasma flow are shown with grey arrows. (Upper left adapted from Belcher 1987; below adapted from Brice & Ioanidis 1970).

Figure 3*b* shows that at the poles the planetary magnetic field lines are open to the solar wind. The solar wind drives a plasma flow across the polar caps and the field lines from the polar region move in the direction of the solar wind flow, being pulled by the solar wind over the poles and back into the extended magnetotail. Conservation of flux requires that field lines are further cut and reconnected in the tail.

The MHD condition of the field being frozen to the flow can be written as $\mathbf{E}+\mathbf{V}\times\mathbf{B}=\mathbf{0}$, which allows the convection electric field to be written $\mathbf{E}_{cv} = -\eta\mathbf{V}_{sw}\times\mathbf{B}_0/R_m^3$ (where η is the efficiency of the reconnection process in harnessing the solar wind momentum, ~0.1 for the Earth). In simple magnetospheric models E_{cv} is assumed constant throughout the magnetosphere. The corresponding circulation is given by the $\mathbf{E}\times\mathbf{B}$ drift,

$V_{cv} = \eta V_{sw}(r/R_m)^3$ where R_m is the magnetopause distance. After being carried tailward at high latitudes, the plasma then drifts towards the equatorial plane and eventually returns in a sunward flow to the dayside magnetopause.

Comparison of the corresponding electric fields indicates whether the magnetospheric circulation is driven primarily by the solar wind or the planet's rotation. Since E_{co} is proportional to R^{-2} and E_{cv} proportional to R^3, it seems reasonable to expect that corotation dominates close to the planet while solar wind driven convection dominates outside a critical distance R_c. Thus the fraction of the magnetosphere that corotates is given by $R_c/R_m = (R_m\Omega/\eta V_{sw})^{1/2}$, which simply means that magnetospheres of rapidly rotating planets with strong magnetic fields are dominated by rotation while the solar wind controls the plasma flow in smaller magnetospheres of slowly rotating planets.

THE EARTH The following is a brief description of the Earth's magnetosphere (Figure 4) which will allow comparison with the giant planet

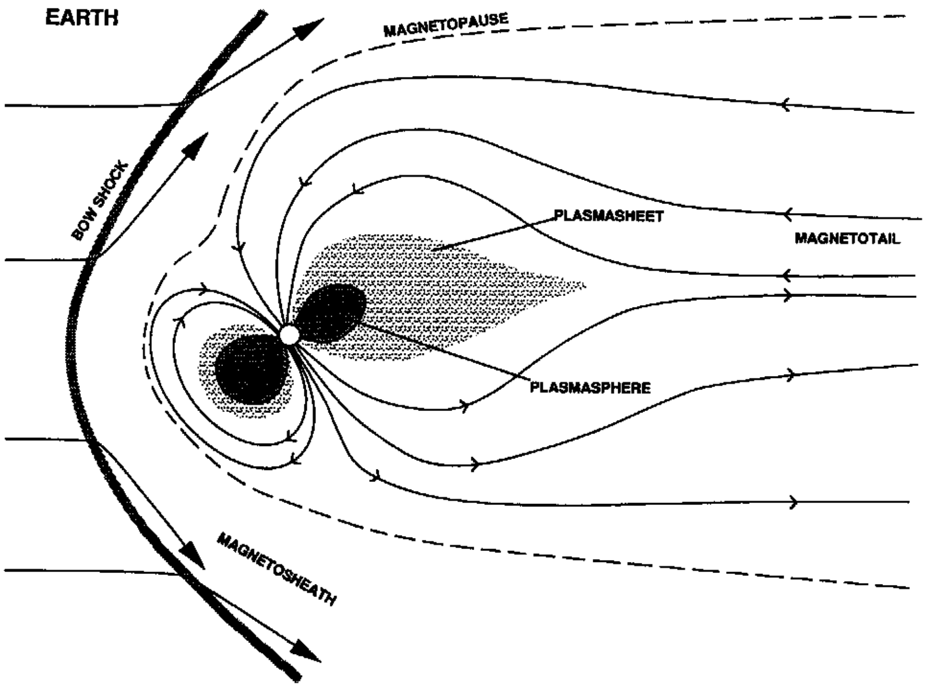


Figure 4 The magnetosphere of the Earth.

magnetospheres. Reviews of the terrestrial magnetosphere can be found in the 1991 IUGG Report and references therein. For the Earth, $R_c/R_m \approx 0.4$ and there exists a region close to the planet where the plasma corotates with the planet, the magnetic field lines remain closed, and large densities of plasma can build up over time. This is the *plasmasphere*. At a distance of about 4 R_E there is a sharp boundary, the *plasmapause*, where the plasma density drops abruptly (from ~ 100 cm^{-3} to ~ 1 cm^{-3}) and outside of which the circulation, driven by the solar wind, is sunward at the equator and antisunward at high latitudes. This means that a large proportion of the Earth's magnetosphere is strongly influenced by the solar wind and will respond to changes in solar wind conditions. In particular, the dayside reconnection rate and hence the convection electric field varies with the orientation of the interplanetary magnetic field, with maximum reconnection occurring when the planetary and solar magnetic fields are oppositely-directed. Under some interplanetary conditions the convection electric field probably results from a purely viscous interaction (which must involve collision-free, micro-scale processes and is poorly understood) between the solar wind and the magnetospheric plasma rather than reconnection. For a given solar wind condition, however, the reconnection on the dayside magnetopause appears to be quasi-steady. By contrast, the kinetic energy of the solar wind that is stored in the tension of stretched magnetic field lines in the tail is violently released episodically in what are known as *magnetospheric substorms*. Oppositely-directed magnetic field lines are believed to reconnect in the center of the magnetotail and the plasma in the reconnected flux tubes is accelerated away from the reconnection point (10–15 R_E). A major focus of studies of the Earth's magnetosphere is understanding the details of how the magnetosphere is coupled to the solar wind and the processes whereby the magnetosphere responds to variations in the interplanetary medium.

JUPITER AND SATURN Long before spacecraft visited the giant planets, theorists estimated R_c/R_m to be much greater than unity for Jupiter and concluded that the magnetosphere of Jupiter would be dominated by rotation throughout and relatively unaffected by the solar wind (Gledhill 1967, Melrose 1967, Brice & Ioannidis 1970). Similarly, Siscoe (1979) predicted that the other giant planet magnetospheres should also be rotation-dominated with $R_c/R_m > 1$. The Voyager Plasma Science instruments confirmed that the bulk motion of the plasma in the magnetospheres of both Jupiter and Saturn is largely azimuthal but measured significant deviations from rigid rotation (McNutt et al 1981, Richardson 1986). The magnetospheres of Jupiter and Saturn are sketched in Figures 5 and 6 respectively. In the case of Jupiter the plasma flow was measured to be

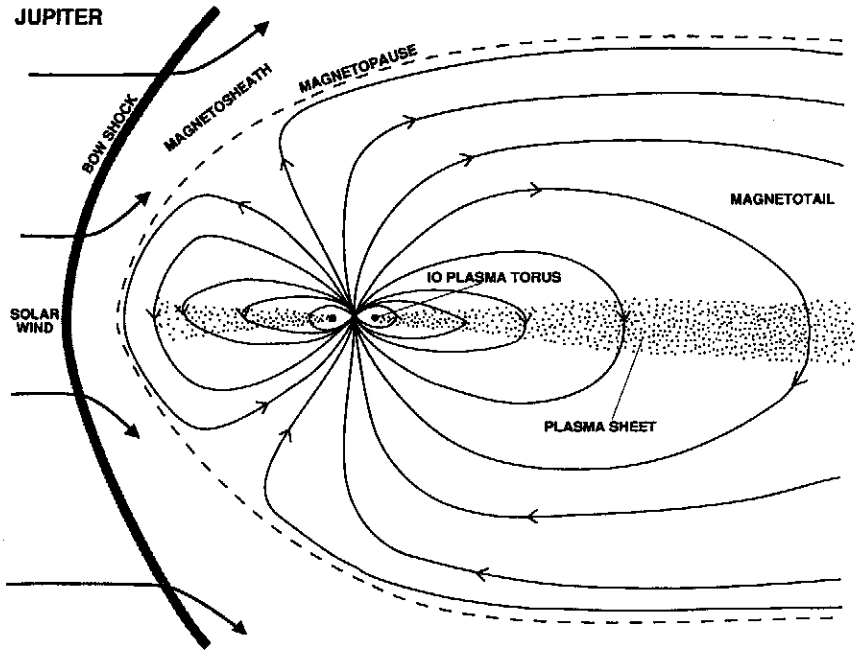


Figure 5 The magnetosphere of Jupiter.

within 1% of rigid corotation in the inner region at 5 R_J (Bagenal 1985b). At larger distances, the Voyager observations confirmed Hill's (1979) prediction that the angular momentum required to accelerate plasma to higher azimuthal velocities in order to maintain corotation with the planet becomes an increasing strain on the frictional coupling between the Jovian ionosphere and neutral atmosphere and the flow lags behind corotation. McNutt et al (1979) reported departure from corotation occurring from about 12 R_J outwards with the azimuthal flow tending towards a constant speed of about 200 km s^{-1} beyond 20 R_J. The mechanical stresses in the magnetosphere that cause this departure from corotation are the large plasma source near Jupiter's satellite Io and the subsequent outward transport of this material (Hill 1980). At Saturn, the observed $\sim$30% deviations of the azimuthal flow from rigid corotation are due to the local production of plasma in the vicinity of Saturn's icy satellites outside $\sim$6 R_S (Richardson 1986). (The characteristics of these magnetospheric plasmas are discussed below.)

The question then arises that if the flow in the bulk of the magnetosphere is azimuthal, what happens in the tail? Spacecraft have passed only through

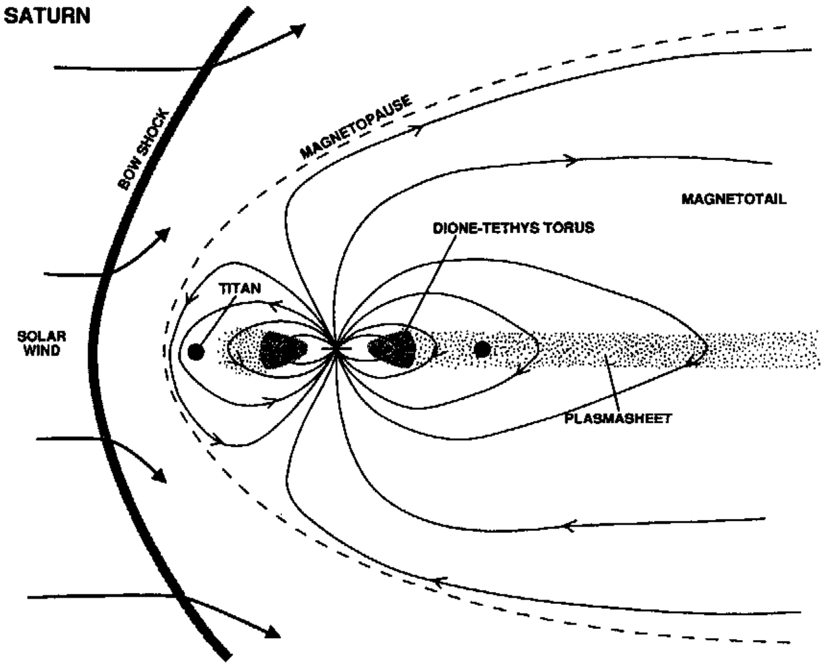


Figure 6 The magnetosphere of Saturn.

the dawn sectors of the Jovian and Saturnian magnetospheres so we can only conjecture about the true structure of their magnetotails. There are two main theories, illustrated in Figure 7. Vasyliunas (1983) proposes a planetary wind model in which at some distance from the planet the kinetic energy of the rotational flow becomes greater than the energy of the magnetic field (i.e. when the corotational speed equals the local Alfvén speed). The flow then "breaks" and reconnects the magnetic field; material is then disconnected from Jupiter and flung down the tail. Alternatively, Cheng & Krimigis (1989) argue that one can just extend the Brice & Ioannidis (1970) corotation-convection model and have solar wind driven convection bringing in solar wind material on the dusk side of the magnetotail and a magnetospheric wind on the dawnside. Whilst Cheng & Krimigis (1989) present the composition of energetic particles that was measured by Voyager as it passed down the dawn magnetotail as evidence supporting their model, we will have to wait until an orbiter such as *Galileo* or *Cassini* passes through the dusk sector to reveal the nature of the magnetotails of these rotation-dominated planets.

There is also the issue of magnetospheric flow near the dayside mag-

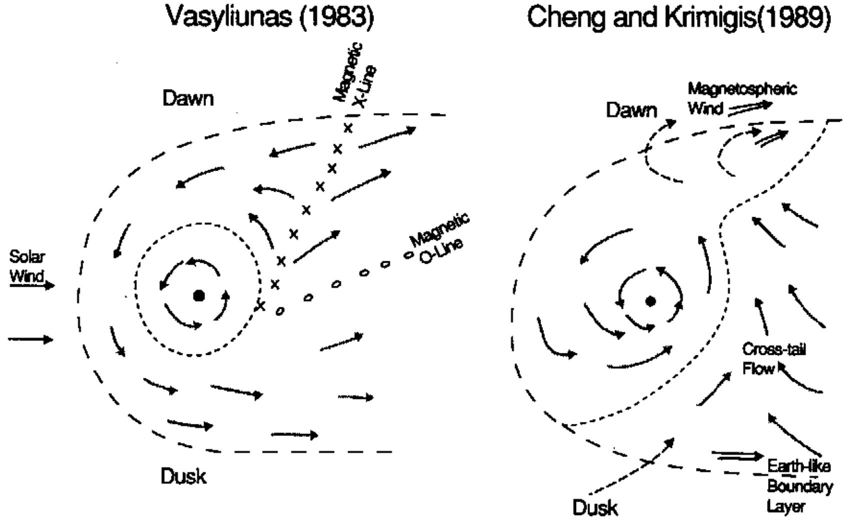


Figure 7 Two models for the configuration of the magnetotails of symmetric, rotation-dominated magnetospheres such as Jupiter and Saturn. (*Left*) From Vasyliunas 1983; (*right*) from Cheng & Krimigis 1990.

netopause. In the afternoon sector one expects the corotational flow to approximately match the magnetosheath flow in both magnitude and direction. One therefore expects little interaction between the interior and exterior flows across the magnetopause (though to date no spacecraft have crossed the afternoon magnetopause and actually measured the flow). In the morning sector the corotation flow is oppositely directed to the solar wind plasma just outside the magnetopause. Strong shears in plasma flow lead to instabilities. Goertz (1983) explains large fluctuations in plasma parameters observed in the outer regions of Saturn's magnetosphere in terms of very turbulent flows with blobs of magnetospheric plasma being detached and carried antisunward by the magnetosheath flow.

Asymmetric Magnetospheres

Early studies were based on experience of Earth, Jupiter, and Saturn and only considered symmetric magnetospheres. Uranus sent magnetospheric theorists back to basics. In the symmetric case, the convection electric field, and hence convective motions, are quasi-steady in the inertial reference frame. Once the magnetic tilt angle becomes appreciable this is no longer true.

URANUS In the case of Uranus where the rotation axis is currently nearly parallel to the solar wind direction, the solar wind driven convection and the direction of planetary rotation are orthogonal and hence decoupled: In the reference frame rotating with Uranus (in which there is no corotation electric field) the solar wind driven convection is quasi-steady and permeates throughout the magnetosphere (Hill 1986, Vasyliunas 1986, Selesnick & Richardson 1986). Thus the plasma in Uranus' magnetosphere corotates with the planet once every 17 hours but on a longer time scale (days) the plasma is circulated through the magnetosphere by the solar wind driven convection. Elements of plasma exhibit helical trajectories, spiraling sunward at the magnetic equator and antisunward at high latitudes. Figure 8 shows two configurations of Uranus' magnetosphere separated by half a planetary rotation. To first approximation, the magnetosphere of Uranus resembles that of the Earth but revolves every 17 hours around the planet-Sun line.

This simple picture was modified by Selesnick & McNutt (1987) to include effects due to drifts of the hot plasma population, which leads to electric currents and partial shielding of the inner region ($<5\ R_U$) from the convection electric field. If the inner region is shielded from the solar wind driven convection then appreciable densities of cold plasma can accumulate. Conversely, magnetospheric plasma that originates in the outer region is deflected around, and hence excluded from, the inner shielded region. Such a quasi-steady shielding model is consistent with the enhanced densities of cold plasma measured in the inner region of Uranus' magnetosphere and the abrupt decrease in hot (keV) plasma inside $\sim 5\ R_U$ (McNutt et al 1987, Selesnick & McNutt 1987). However, Sittler et al

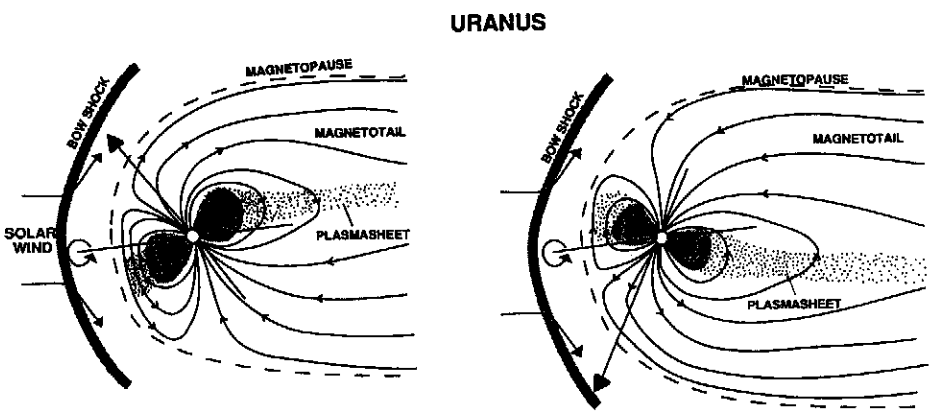


Figure 8 The magnetosphere of Uranus. Left and right are separated by half a planetary rotation.

(1987) and McNutt et al (1987) point out that features of the Voyager plasma data are also reminiscent of the highly time-dependent substorms in the Earth's magnetosphere. Further, Mauk et al (1987) and Cheng et al (1987) note substorm-like signatures in the energetic particle data at Uranus. By developing his model of convection to include the nondipolar magnetic field and time-dependent injection of plasma from the magnetotail, Selesnick (1988) is able to match many of the features observed by Voyager. Nevertheless, the few hours of data obtained on a single passage just give us a glimpse of the Uranian system. If, as we suspect, the magnetosphere of Uranus is as dynamic as the Earth's, then a statistical study of data obtained on multiple passages through the region will be necessary to properly distinguish spatial and temporal variations.

Uranus' magnetotail shows strong similarities to the Earth's magnetotail: The lobes of oppositely-directed magnetic field are separated by a cross-tail current and a sheet of enhanced plasma density (Ness et al 1986, Bridge et al 1986, Voigt et al 1987, Behannon et al 1987). The plasma sheet lies in the magnetic equatorial plane near Uranus but bends parallel to the solar wind flow tailward of distances beyond 10–15 R_U. The fundamental difference between the Uranian magnetotail and that of the Earth is that the whole tail structure rotates in space approximately about the Uranus-Sun line because of the near-alignment of the Uranian spin axis with the solar wind flow. For further discussion of the configuration of Uranus' magnetosphere see the review by Belcher et al (1991) and references therein.

NEPTUNE If a planetary rotation axis is not approximately aligned with either the magnetic dipole axis or the solar wind flow direction then there exists no reference frame in which the plasma flow is steady (Selesnick 1990). At the time of the Voyager 2 encounter in 1989, Neptune's northern hemisphere was close to midwinter with the rotation axis tipped 113° from the Sun, i.e. 67° from the radial, solar wind direction. The 47° tilt of the magnetic dipole means that the angle between the solar wind and the dipole axis changes between 20° and 114° over the 16.1 hour planetary rotation. When the angle is near 90° the configuration is, momentarily, symmetrical like Earth, Jupiter, and Saturn. When the angle is small we have a unique configuration with the magnetic axis pointed "pole-on" into the solar wind, a configuration that was expected for Uranus before Voyager 2 found a large dipole tilt (Siscoe 1975, Voigt et al 1983). These configurations lead to very different magnetic field topologies. Complete reconfiguring of the magnetosphere must occur every planetary rotation (Ness et al 1989, Belcher et al 1989).

Figure 9 shows the two extreme configurations that occur 8 hours

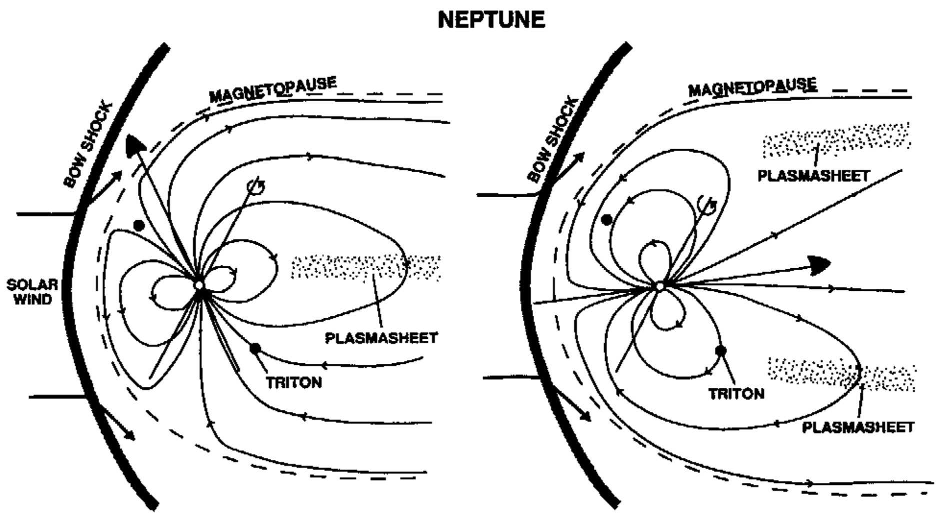


Figure 9 The magnetosphere of Neptune. Left and right are separated by half a planetary rotation.

apart. A theoretical model of plasma convection in Neptune's changing magnetosphere developed by Selesnick (1990) can be summarized as follows. The corotation velocity is everywhere greater than convection but convection has a cumulative effect over several planetary rotations, leading to a net sunward transport of plasma in the magnetic equatorial plane. The maximum reconnection of solar and planetary magnetic fields occurs for the "Earth-like" configuration. During the "pole-on" configuration there is only a small region of the magnetopause where the planetary and solar fields are antiparallel. The occurrence of each configuration corresponds to a specific magnetic longitude passing through local noon. Therefore, in the corotating reference frame convection varies systematically with time, being stronger when the longitudes corresponding to the Earth-like configuration cross local noon. Thus an element of plasma that was at local noon during Earth-like configuration will drift away from Neptune while an element that was at midnight will drift (more slowly) towards the planet. Viewed from the nonrotating reference frame the plasma spirals inward or outward depending on its location at the time of Earth-like configuration. Therefore, in Selesnick's (1990) model, convection and hence variations in density are expected to be strongly longitude dependent. Alternatively, Hill & Dessler (1990) assume a longitudinal asymmetry in the distribution of plasma and derive a four-cell convection pattern that corotates with the planet. Richardson et al (1991) point out, however, that while the above convection models predict transport rates comparable to those required to match the Voyager plasma data ($\tau \approx 1$ day), the observations show no longitudinal asymmetry in the plasma density and indicate only inward transport of plasma which is inconsistent with both models.

The dramatic changes in the configuration of the magnetotail occurring every planetary rotation must further complicate the dynamics of Neptune's magnetosphere (Belcher et al 1989, Ness et al 1989, Voigt & Ness 1990). During the Earth-like configuration the magnetotail is like the Earth's with oppositely-directed magnetic fields separated by a current sheet. When the magnetosphere is pole-on, the magnetotail has a cylindrical configuration with planetward-directed field on the outside and field lines leaving the planet on the inside separated by a cylindrical current sheet.

THERMAL PLASMA CHARACTERISTICS

It is rather misleading to describe a magnetosphere as an empty cavity from which the solar wind is excluded. Magnetospheres contain considerable amounts of plasma which have "leaked in" from various sources (Table 2). Firstly, the magnetopause is not entirely "plasma-tight." Solar wind plasma enters through the polar cusp and, whenever the interplanetary magnetic field has a component antiparallel to the planetary field at the

Table 2 Plasma characteristics of planetary magnetospheres

	Earth	Jupiter	Saturn	Uranus	Neptune
Maximum Density (cm^{-3})	1-4000	>3000	~100	3	2
Primary Sources	O^+, H^+ Ionosphere[a]	O^{n+}, S^{n+} Io	O^+, H_2O^+ H^+ Dione, Tethys	H^+ H cloud	N^+, H^+ Triton
Secondary Sources	H^+ Solar wind[a]	H Ionosphere	N^+, H^+ Titan	H^+ Solar wind	H^+ Solar wind
Source Strength (ions/s) (kg/s)	2×10^{26} 5	$>10^{28}$ 700	10^{26} 2	10^{25} 0.02	10^{25} 0.2
Lifetime	days[b] hours[c]	10-100 days	30 days - years	1-30 days	~1 day

[a] Chappell et al (1987).
[b] Filling time for plasmasphere.
[c] Convective time outside plasmapause.

magnetopause, magnetic reconnection is likely to occur and solar wind plasma will leak into the magnetosphere. Secondly, although ionospheric plasma is generally cold and gravitationally bound to the planet, a small fraction has sufficient energy to escape up magnetic field lines and into the magnetosphere. Thirdly, the interaction of magnetospheric plasma with any natural satellites that are embedded in the magnetosphere can generate significant quantities of plasma.

Before discussing the plasma characteristics of each giant planet in turn, it should be noted that the bulk of magnetospheric plasmas are generally found not far from equilibrium, i.e. their particle distribution functions are observed to be approximately Maxwellian (though the ion and electron populations often have different temperatures). This fact is remarkable considering that the sources are usually expected to be monoenergetic and time scales for equilibration by means of Coulomb collisions are usually much longer than transport time scales. At the same time, planetary magnetospheres support a variety of plasma waves which have various energy sources and cover a wide range of frequencies (see the review by Kurth & Gurnett 1991). Interactions between these waves and particle populations are thought to be responsible for thermalizing the bulk of the plasma as well as accelerating or scattering particles at higher energies. For, in addition to the thermal populations (which make up the bulk of the plasma by number density), all planetary magnetospheres contain populations of energetic (MeV) particles which often dominate the energy density (discussed further in a separate section below).

Jupiter

The study of Jupiter's magnetospheric plasma has an interesting history. When Burke & Franklin (1955) discovered Jupiter to be a source of radio emission, it was soon realized that this radio emission must come from energetic charged particles in a strong magnetic field. This remarkable discovery came before Van Allen's detection of the Earth's radiation belts and the in situ verification of the solar wind (Neugerbauer & Snyder 1962). A more puzzling discovery came a few years later when Bigg (1964) revealed that the decametric component of the Jovian radio emission was influenced by Io, the innermost of the four Galilean satellites. The decimetric component of the radio emission was assumed to be synchrotron radiation from electrons with energies of ~ 10 MeV that gyrate around dipolar magnetic field lines at a distance of a few Jovian radii. This basic picture of a strong magnetic field trapping a large, energetic particle population was confirmed by Pioneers 10 and 11 which reached Jupiter in 1973 and 1974, respectively. The Pioneers also revealed that farther from the planet the magnetic field is considerably stretched out so that the

Jovian magnetosphere is shaped more like a disk than a sphere. Although the large size and radial distension implied the presence of a substantial amount of plasma at lower energies, the Pioneer plasma detector provided little information on the thermal population. Nevertheless, the theorists had already come out strongly in favor of a magnetosphere dominated by the planet's rotation (Gledhill 1967, Melrose 1967, Brice & Ioannidis 1970). A few months before the Pioneer 10 encounter, Brown (1974) detected optical emission from neutral sodium atoms in the vicinity of Io using a ground-based telescope. The first direct evidence of the presence of high densities of ionized material at low energies near Jupiter came with the discovery by Kupo et al (1976) of optical emission from S^+ ions. Mekler et al (1977) and Brown (1976), borrowing techniques from studies of more remote astronomical gaseous nebulae, concluded that the S^+ emission comes from a dense (500–3000 cm^{-3}) ring of cold (few eV) plasma that corotates with Jupiter inside the orbit of Io. In 1979 the Voyager 1 spacecraft confirmed that Io is the major source of plasma in the Jovian magnetosphere—a fact that seemed less surprising when the Voyager cameras revealed the satellite's active volcanoes. Bright ultraviolet emission (Broadfoot et al 1979) and local plasma measurements (Bridge et al 1979) revealed an extensive torus of hotter ($\sim$80 eV) plasma outside the inner ring of cold plasma (Figure 10).

THE IO-PLASMA INTERACTION Bigg's observation that Io modulates the intensity of Jovian decametric radio emission initiated many early models of the satellite's interaction with the magnetospheric plasma (Marshall &

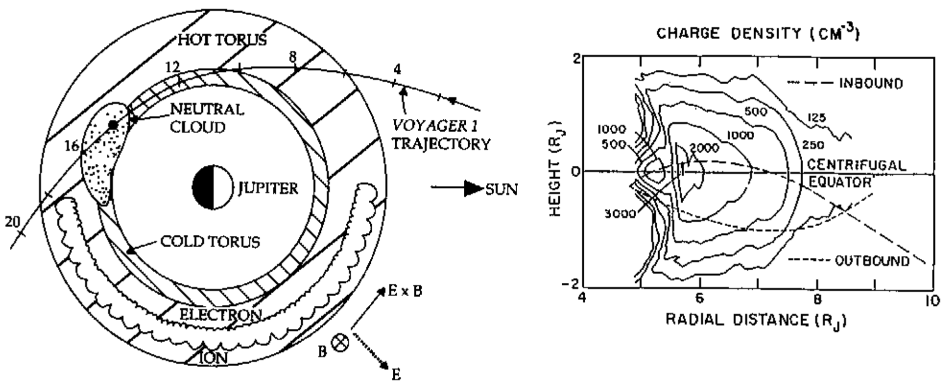


Figure 10 (*Left*) Sketch in Jupiter's equatorial plane of the Voyager 1 trajectory through the Io plasma torus. (From Belcher 1987.) (*Right*) Contours of local charge density in the Io plasma torus derived from data obtained on the inbound trajectory (*long dashes*) of the Voyager 1 spacecraft. (From Bagenal et al 1985.)

Libby 1967, Piddington & Drake 1968, Goldreich & Lynden-Bell 1969, Gurnett 1972, Goertz & Deift 1973). These early studies assumed Io to be a perfect conductor and the ambient plasma density to be very low. They examined how Io's motion in the planetary magnetic field might cause the satellite to act as a unipolar generator and investigated the possibility that large field-aligned currents might directly connect the satellite to the planet. Following Drell's description of a large conducting body generating Alfvén waves as it moves through a magnetic field (Drell et al 1965), Marshall & Libby (1967) were the first to propose that Io might generate large amplitude Alfvén waves that propagate along the magnetic field to the ionosphere of Jupiter where the radio bursts are triggered. However, in applying the theory to Io, the early theorists were hampered by ignorance of the properties of Io and the surrounding plasma.

The perturbations of the magnetic field and plasma flow that were measured in the vicinity of Io when Voyager 1 passed beneath the satellite confirmed the theoretical expectations of a strong interaction between Io and the magnetospheric plasma (Ness et al 1979, Bridge et al 1979). Indeed, further analysis indicated that an Alfvénic disturbance was radiated by Io, carrying a 10^6 amp field-aligned current towards the ionosphere of Jupiter (Neubauer 1980, Belcher et al 1981, Acuna et al 1981, Barnett 1986). Moreover, the observed high plasma densities implied that the propagation speed of Alfvén waves is small in the torus (Bagenal & Sullivan 1981). This means that by the time an Alfvén wave has traveled from Io to Jupiter's ionosphere (where it is reflected) and back, Io has moved along its orbit so that the field-aligned currents do not form a closed loop through Io as was first suggested by Goldreich & Lynden-Bell (1969) but rather form open-ended Alfvén wings similar to Drell's model (reviewed by Belcher 1987).

Although it seems that to first approximation Io is a good conductor, in detail the Io-plasma interaction is complicated by the presence of Io's atmosphere (reviewed by Schneider et al 1989 and Cheng & Johnson 1989). Io's volcanoes are believed to be ultimately responsible for a tenuous ($\sim 10^{-9}$ bar) atmosphere of mostly SO_2, either via direct venting or sublimation of volcanic frosts deposited on the surface. The atmosphere is probably patchy and is expected to vary with Io's volcanic activity (e.g. Ingersoll 1989, Moreno et al 1991). Io orbits well inside Jupiter's magnetosphere, embedded in the corotating magnetospheric plasma and high fluxes of energetic particles. The issue is whether these particles reach the surface of Io. Theoretical studies (Sieveka & Johnson 1985, McGrath & Johnson 1987, Moreno et al 1991) and recent observations (Ballester et al 1990) suggest that the atmosphere is collisionally thick (with an exobase at $<0.5\ R_{Io}$), particularly on the dayside and/or above volcanic plumes, so that the impinging charged particles do not reach the surface but collide with atmospheric constituents, heating the upper atmosphere (Johnson 1989) and sputtering energetic atoms and molecules (at a rate of 10^{28}–10^{29} s^{-1}), and forming an extended neutral corona around Io. Presumably, the main constituents of this sputter-corona are products of SO_2 dissociation. Emissions from extended clouds of neutral oxygen (Brown 1981) and sulfur (Durrance et al 1983) have been detected. However, because of their efficient scattering of sunlight, two minor constituents, sodium and potassium, are more readily visible. Since its discovery in 1973 (Brown 1974), the bright sodium cloud has been studied as a tracer of neutral-ion processes in the vicinity of Io (see reviews by Brown et al 1983; Schneider et al 1989, 1991a). Most recently, Schneider et al (1991b) have interpreted jet-like features in images of the sodium cloud as evidence that a substantial amount of sodium escapes in the form of sodium-bearing molecules (rather than sodium atoms). Two important implications of this observation are that the impinging plasma must penetrate deep into Io's atmosphere and that a substantial amount of molecular SO_2 might also be sputtered off rather than just its dissociation products.

The size of Io's neutral sputter-corona is limited by rapid electron-impact ionization and charge-exchange with the corotating ions. This leads to a fundamental problem of stability (Huang & Siscoe 1987, but also see Cheng 1988). The problem is well-stated by Schneider et al (1989): "At the core of the complex reactions between ions and neutrals is the basic fact that the plasma torus generates itself: the corotating ions lift the neutrals off Io, and the electrons ionize them. In this narrow view, we have an unstable positive feedback loop, where ions beget more ions, ad infinitum." Since emissions from the neutral sodium cloud and the torus plasma have not been increasing over the years, there must be a mechanism stabilizing the system. The three main candidate mechanisms for maintaining stability are: (*a*) a means of transporting plasma away from Io, such as the fluxtube interchange instability, that depends nonlinearly on plasma density so that the removal rate grows faster than the source as density increases (Huang & Siscoe 1987), (*b*) the decrease in electron temperature at higher densities which leads to a decreasing ionization rate, limiting the source (Barbosa et al 1983, Smith & Strobel 1985), and (*c*) the atmosphere of Io acts as a buffer by controlling the supply of neutrals either because an increase in flux of corotating ions leads to a lower exobase and smaller effective impact cross-section (Johnson 1989) or because increased ionization in the vicinity of Io leads to further deflection and cooling of the flow around Io (Bagenal 1989, Linker et al 1989). In order to understand the complex processes that couple Io and its atmosphere to the magnetospheric plasma we need detailed models of the Io-plasma interaction [e.g. further development of

3-dimensional MHD numerical simulations similar to that of Linker et al (1988, 1989)] as well as measurements of the response of neutral clouds and the Io torus to changes in volcanic activity (Schneider et al 1989).

THE IO PLASMA TORUS As the Voyager spacecraft approached Jupiter the ultraviolet spectrometer detected powerful emission (3–6 × 10^{12} Watts) from sulfur and oxygen ions in a toroidal region encompassing the orbit of Io (see reviews by Brown et al 1983 and Strobel 1989). When the Voyager 1 spacecraft flew though the plasma torus, the Plasma Science instrument made local measurements of both the electrons and the various ionic species: $O^{+,2+}$, $S^{+,2+,3+}$, and an ion with a mass/charge ratio of 64, which could be SO_2^+ and/or S_2^+ (see reviews by Belcher 1983 and Bagenal 1989). From the plasma measurements it is clear that the Io plasma torus is divided into two distinct regions with a sharp boundary at 5.7 R_J, inside Io's orbit at 5.9 R_J (see Figure 10). The large outer region of the warmer (~80 eV) plasma produces the UV and much of the optical emissions while the colder (~few eV) plasma inside emits only at optical wavelengths.

Observations confirm early predictions that the distribution of plasma along magnetic field lines is limited by the strong centrifugal forces which tend to confine the plasma to the region of the field line farthest from Jupiter's spin axis—the centrifugal equator (Gledhill 1967). To first approximation, the plasma density decreases exponentially with distance from the centrifugal equator $n(z) = n_0 \exp -(z/H)^2$, where the scale height H is given by $H = (2kT_i/3m_i\Omega^2)^{1/2}$ for a spin rate of Ω and ions of mass m_i and temperature T_i (Hill & Michel 1976). Thus the warmer ions in the outer region of the torus have a large scale height and are more spread out along the field than the cold ions inside Io's orbit (see Figure 10).

The plasma is either produced directly in the interaction between Io's atmosphere and the magnetospheric plasma or by ionization of the extended neutral clouds. The lack of enhanced UV emission near Io limits the source strength from the first mechanism. It is estimated that a total of 10^{28}–10^{29} ions must be produced by Io per second to maintain the plasma torus. In either case, when the neutrals are ionized they experience a Lorentz force as a result of their motion relative to the local magnetic field; this force causes the ions to gyrate about the magnetic field at a speed equal to the magnitude of the neutral's initial velocity relative to the surrounding plasma. The ion is accelerated until its guiding center motion matches the plasma rest frame, corotating with Jupiter. Because a particle's gyroradius is mass-dependent, the new ion and its electron are separated after ionization. Hence there is a radial current caused by the ions being "picked-up" by the magnetic field. This radial current across the torus is linked by field-aligned currents to the ionosphere of Jupiter where the

$\mathbf{J} \times \mathbf{B}$ force is in the opposite direction to the planet's rotation (see Figure 3*a* and 10 *left*). Thus the planet's angular momentum is tapped electrodynamically by the newly ionized plasma.

Oxygen and sulfur ions picked-up by the magnetic field gain gyroenergies of 260 and 520 eV respectively. The initial velocity distributions are expected to be highly anisotropic (Siscoe 1977) and unstable to the generation of plasma waves (e.g. Barbosa et al 1985, Barbosa & Kruth 1990), and the different ionic species and electrons are not in thermodynamic equilibrium. One expects Coulomb collisions and wave-particle interactions to change the distribution to a more stable one: firstly, to pitch-angle scatter particles into an isotropic distribution; secondly, to produce equipartition of energy for each species (i.e. Maxwellian distributions); and thirdly, to produce equipartition of energy between species of different mass. Inside 5.7 R_J, the ion species are close to equilibrium having Maxwellian distributions with the same temperature (Bagenal 1985b). Although the separate species' distribution functions are not resolved in the Voyager data, in the warm region of the torus complete thermal equilibrium is unlikely because the time scales for equilibration are probably longer or of the same order as the time scale for transport (Bagenal & Sullivan 1981, Bagenal 1989).

While initial calculations of the energy injection rate from the ionization of new material at the pick-up energy were able to balance the radiation output (Barbosa et al 1983, Smith & Strobel 1985), Shemansky (1988) calculates, using more accurate (higher) values for the radiative efficiency of sulfur ions, that an appreciable additional source of energy is required to explain the observed plasma conditions. Proposed solutions to this "energy crisis" currently include enhanced charge-exchange reactions in Io's exosphere (Shemansky 1988, but also see Bagenal 1989), collisional heating by inwardly-diffusing energetic particles (Smith et al 1988), and local magnetic pumping (Ip 1990). Attempts to model the cold, inner torus (Richardson & Siscoe 1983, Barbosa & Moreno 1988) have encountered difficulties explaining (*a*) substantial densities of O^{2+} when the electron temperature is < 1 eV; (*b*) the presence of SO_2^+ (or S_2^+) ions at 5.3 R_J when one expects any molecules sputtered to be rapidly dissociated near Io; and (*c*) the presence of a hot component to the ion distribution indicating a local source of pick-up ions. These models are far from reproducing the detailed measurements made by Voyager (Bagenal 1985b, 1989) and from ground-based telescopes (Brown et al 1983, Trauger 1984).

PLASMA SHEET While the high densities (> 1000 cm^{-3}) are confined to a toroidal region within ~ 1 R_J of Io's orbit, the iogenic material extends out to at least 40 R_J, forming a thin (< 5 R_J thick) sheet of warm (10's of eV) plasma with densities decreasing to a few per cm^{-3} by 20 R_J and dominated by sulfur and oxygen ions (Belcher 1983). This is Gledhill's (1967) magnetodisc, where the centrifugal forces on the corotating plasma stretch out the magnetic field at the equator. In addition to the warm (10's of eV) iogenic plasma there is a hot ($\sim$30 keV) thermal plasma (with Maxwellian distributions) in the middle magnetosphere, beyond 10 R_J (see the review by Krimigis & Roelof 1983). This hot plasma has an energy density greater than the local magnetic field (i.e. $\beta > 1$) and inflates the magnetosphere, making it flatter at the poles (Engle 1991) and more compressible than a vacuum dipole magnetosphere (Caudal 1986). In a self-consistent model of the magnetodisc, Caudal (1986) finds that the radial Maxwell stresses of the stretched magnetic field are balanced by a combination of pressure gradient forces from the hot plasma ($\sim$70%) and to a lesser extent ($\sim$30% overall) centrifugal stresses exerted by the warm plasma (see also McNutt 1983, Mauk & Krimigis 1987, and Khurana & Kivelson 1989a).

The intriguing issue is, What is the source of the hot plasma? The density gradient indicates a source in the outer magnetosphere (Krimigis & Roelof 1983). The ion composition is not measured directly at the keV energies of the hot thermal plasma, but at higher energies the sulfur and oxygen concentrations were found to be strongly enhanced over solar abundances, implicating Io. Furthermore, analyses of plasma waves (Khurana & Kivelson 1989b) and the structure of the plasma sheet (Caudal & Connerney 1989) indicate that protons comprise only 20–50% of the composition which rules out the solar wind as the main source. Alternatively, Barbosa et al (1984) propose that the torus ions are recycled in the outer magnetosphere. When corotating ions in the torus undergo charge-exchange reactions with Io's neutral clouds, the neutralized atom keeps most of its momentum but is no longer confined by the magnetic field and hence is ejected from the Jovian system. Clear evidence of this wind of fast neutrals is provided by recent observations of a faint flaring disk of neutral sodium atoms extending out to at least 400 R_J (Mendillo et al 1990). Eviatar & Barbosa (1984) estimate that about 2% of the neutral sulfur and oxygen wind will be ionized in the outer magnetosphere where they will pick up keV energies corresponding to the local azimuthal speed of 300 km s^{-1}. Adiabatic heating of such ions as they are transported inwards can provide the energies of the hot plasma in the plasma sheet. To provide the observed high fluxes of particles at MeV energies, however, a variety of acceleration processes have been proposed, reviewed in Dessler (1983) and by McNutt (1991).

Currently, we are left with a double puzzle: The warm plasma does not cool adiabatically as it expands out into the magnetosphere (one expects plasma to cool from 80 eV at 6 R_J to 2 eV at 20 R_J), and Caudal & Connerney (1989) find that as the hot (20 keV) plasma is transported inwards the change in pressure with flux-tube volume is not adiabatic ($\gamma < 1$ outside $10R_J$ (see also Paranicas et al 1990).

RADIAL TRANSPORT The distribution of plasma in the inner and middle magnetosphere, particularly the torus structure and the presence of iogenic plasma in the middle magnetosphere, indicates that plasma is being transported outward, perpendicular to the magnetic field. Furthermore, the sharp boundary close to Io's orbit between the two regions of the torus suggests a sharp change from slow ($\tau \approx$ year) inward diffusion inside 5.7 R_J to rapid ($\tau \approx$ 10–100 days) outward diffusion outside 5.7 R_J, requiring two mechanisms for radial transport (Richardson et al 1980). The situation is summarized by Fazakerley (1990) as follows (abridged):

> The transport mechanism operating inside Io's orbit is consistent with diffusion driven by fluctuations in Jupiter's ionosphere, which was originally proposed to account for the inward transport of energetic particles supplying the Jovian radiation belts. The second (outward) transport mechanism is not understood but it is required to: tap centrifugal potential energy, transport iogenic plasma more rapidly than ionospheric driven diffusion, and produce the observed variations in the rate of transport with distance. Most models are variations of MHD centrifugally-driven interchange motion, ranging from large-scale convection systems to transport by a multitude of small, independent flux tubes (see review by McNutt 1991). However, it is difficult to reconcile the long-lasting azimuthal symmetry of the Io torus with the existence of large scale convection cells. At the same time, small flux tubes are unlikely to remain as coherent structures on the time scales envisaged for interchange motions in MHD models, due to particle drift motion. The most serious difficulty with (pure) MHD models, however, is that Voyager observations indicate that fluctuations in the density of iogenic plasma are too slight, on all length scales, to be compatible with any *strictly* MHD interchange theories (Richardson & McNutt 1987). Moreover, both the ionospheric dynamo model and the family of MHD models assume adiabatic motion and hence fail to account for the rise in temperature with distance, which has been observed in the torus and plasma sheet.

The transport mechanism proposed by Fazakerley (1990) (short wavelength interchange transport driven by electrostatic drift waves) is one in a spate of recent studies that invoke *non*-MHD processes (either on their own or in conjunction with MHD interchange) to circumvent the limitations imposed by Richardson & McNutt (1987). [These studies are too numerous to cite and are summarized by McNutt (1991).] At the same time, Cheng & Johnson (1989) argue that the Richardson & McNutt (1987) observations do not rule out all MHD interchange models but may just put a limit on the diffusion rate. Currently, the mechanism for radial transport and the source of hot plasma in the middle magnetosphere remain the two (probably related) major unsolved issues of the Jovian magnetosphere.

Saturn

In the two years between September 1979 and August 1981 the magnetosphere of Saturn was explored by three spacecraft—Pioneer 11 and Voyagers 1 & 2 (see reviews by Scarf et al 1984 and Schardt et al 1984). Overall, Saturn's magnetosphere was found to be similar to the Jovian magnetosphere: Satellites are the major source of magnetospheric plasma and the plasma dynamics are dominated by the planet's rotation. Nevertheless, the magnetosphere of Saturn is considerably smaller and the multiple sources of plasma much weaker and less distinct than Io. Moreover, Saturn's magnetosphere is less compressible than Jupiter's. The dayside magnetopause is close to the Chapman-Ferraro distance and varies as $p^{-1/6}$ with the solar wind pressure. This behavior indicates that the planetary field stands off the solar wind with little contribution from the internal plasma pressure.

The magnetosphere of Saturn is separated by a boundary at about 15 R_S into two regions: an inner region where the plasma density and temperature vary smoothly with distance and an outer region where the plasma densities and temperatures vary erratically. While there is wide agreement that the sources of plasma in the inner region of the magnetosphere are the icy satellites Dione and Tethys (with lesser contributions from Rhea, the small inner satellites, and the rings), there is strong debate over the source and loss processes. In the outer region, debate also remains about the role of Titan.

DIONE-TETHYS TORUS The icy satellites of Saturn are continuously bombarded by energetic particles, corotating plasma, and solar radiation, which sputter off substantial amounts of water from the surfaces and form a disk-shaped cloud in Saturn's equatorial plane of neutral molecular and atomic products of the dissociation of H_2O (Johnson et al 1989). It is agreed that the ionization of these neutrals provides the observed plasma between 4 and 8 R_S which has a density of $\sim$few cm^{-3}, a temperature of $\sim$10's of eV, and comprises $\sim$20% light ions (mass 1–2) and $\sim$80% heavy ion species with masses between 14 and 18 (Richardson 1986). Theoretical calculations of Richardson et al (1986) predict an ion composition of light ions (75% H^+, 25% H_2^+) and heavy ions (40% O^+, 40% H_2O^+, 18% OH^+, and 2% O_2^+). In their model, which assumes slow radial transport ($\tau \approx$ years), the densities inward of $\sim$8 R_S are limited by collisional processes with the neutral water vapor cloud (dissociative recombination of the molecular ions and charge exchange for the atomic ions) with radial transport as the major loss mechanism outside 8 R_S. Barbosa (1990), on the other hand, argues for fast radial diffusion ($\tau \approx 30$ days) and a predominantly O^+ plasma. While the Voyager plasma instrument could easily distinguish light from heavy ions, the mass resolution is insufficient to distinguish between masses 16 to 18. Clearly, the issue of radial transport is again a critical one at Saturn as it is at Jupiter. While signatures in energetic particle data of satellite absorption provide estimates of radial transport rates for MeV particles, these estimates span orders of magnitude (see Barbosa 1990 as well as review by Van Allen 1984). Moreover, the transport mechanism (as yet unknown) may be energy-dependent.

In the outer region of Saturn's magnetosphere, the variability in plasma properties have several explanations. Schardt et al (1984) suggests a response to solar wind variations. Goertz (1983) proposes that blobs of denser, colder magnetospheric plasma are being detached and swept away in the turbulent (dawn sector) region where there is a strong shear between the corotation inside the magnetosphere and the antisunward magnetosheath flow. An alternative explanation presented by Eviatar et al (1982) is that the dense material comes from Titan.

TITAN When Voyager 1 flew close to Titan it passed through a "wake" downstream of the satellite in the magnetospheric flow. Strong perturbations of the magnetic field and plasma flow were measured and ions with mass 28 (probably N_2^+ or H_2CN^+) were detected indicating that 10^{24} ions s^{-1} are produced in the complex interaction of the magnetosphere with Titan's thick atmosphere (see the review by Neubauer et al 1984). However, there is debate over whether Titan is the major source of plasma for the outer magnetosphere. First of all, Titan's overall role in the magnetosphere of Saturn is limited by the fact that its 20.3 R_S orbit places Titan just beyond the average 18.8 R_S subsolar stand-off distance and hence Titan often spends part of its orbit outside the magnetopause (Slavin et al 1985). Moreover, Richardson (1986) claims a better fit to the ion spectra in the outer magnetosphere with water group ions (masses 16–18) coming from the icy satellites than with N^+ (mass 14) from Titan. The problem that O^+ ions should be rapidly removed by the resonant charge-exchange with neutral hydrogen detected at Titan's orbit (Broadfoot et al 1981) is raised by Shemansky et al (1985) who conclude that the neutral hydrogen cloud is much denser and extends from Saturn's atmosphere outwards. Eviatar & Richardson (1990) may have found a solution to this dilemma by suggesting that the major ion is H_2O^+ or H_3O^+ (rather than O^+) which has a longer lifetime against charge-exchange with neutral hydrogen. Meanwhile, Barbosa (1987, 1990) argues that a neutral cloud of nitrogen extending from Titan's exosphere is a source of N+ ions in the outer magnetosphere.

RINGS Inside $\sim 4\ R_S$ the plasma temperature drops and the density (~ 100 cm^{-3}) is concentrated in a $<0.5\ R_S$ thin sheet in Saturn's equatorial plane (Bridge et al 1982, Richardson & Sittler 1990). The low plasma temperatures have been ascribed to interactions with ring material. Eviatar & Richardson (1990) propose that water ions form a dense "ionosphere" above Saturn's rings. This could explain several other puzzles of the Saturnian system such as the radiative cooling of plasma inside the orbit of Tethys which allows the E-ring to survive in the plasma gap between Tethys and the main rings. Investigations of magnetospheric processes associated with an extended ring system of particulate matter form a new area of research. If electrodynamic processes are responsible for certain phenomena observed in Saturn's rings then they may play a role in the cosmogeny of the ring system (see reviews by Mendis et al 1984 and Esposito 1993).

Uranus

Two factors make Uranus' magnetosphere rather empty: There are only a few, small icy satellites and the solar wind driven convection quickly circulates material through the magnetosphere in a few days (for reviews of Uranus' magnetosphere see Bergstrahl et al 1991). The low-density plasma was observed to be all protons, with an upper limit of 10^{-2} cm^{-3} on heavy ions, which is consistent with low sputtering rates for the icy satellites (Cheng 1987). There are two distinct plasma populations: a cold population (10's of eV) that is observed throughout the magnetosphere reaching maximum densities of about 2 cm^{-3} and a hot (keV) population that appears to be excluded from the region inside 5 R_U (sketched in Figure 8).

There are two possible sources of the low-energy plasma: ionization of the unusually dense neutral hydrogen corona of Uranus (Broadfoot et al 1986) and outflow of cold plasma from Uranus' ionosphere. McNutt et al (1987) estimate that a convection time of 1–10 days is consistent with a source strength of 10^{25} s^{-1} by electron impact ionization of the neutral hydrogen corona and the observed densities of 0.1–1 cm^{-3}. Cheng (1987) estimates that the outflow of ionospheric plasma could be a comparable source for residence times of 30 days and puts an upper limit on the amount of solar wind plasma that reaches the inner magnetosphere (<6 R_U) at 10^{-5} of the solar wind hitting the magnetosphere. Cheng (1987) concludes that most of the solar wind material that enters is transported by the convection and may not reach the inner magnetosphere.

The spatial distribution and energy spectrum of the hot (keV) population are consistent with ionization of more distant regions of the hydrogen cloud (where the ions pick up larger corotational energies) followed by adiabatic heating due to compression while being convected inward from the nightside of the magnetosphere (Selesnick & McNutt 1987). Alternatively, one should note that in the inner regions of the Earth's plasma sheet one finds keV material (including O^+ ions) that has escaped from the ionosphere at high latitudes and been convected towards the equator in the inner magnetotail where it is heated by adiabatic compression in the sunward return flow of the solar wind driven convection (Cowley 1980). Mauk et al (1987) point out several features of the energetic particle data obtained in the plasma sheet and magnetotail at Uranus that are reminiscent of the Earth. At Uranus, unfortunately, the same ion species, H^+, is produced from the solar wind, the ionosphere, and the neutral hydrogen corona so we have to work harder to test if Uranus' magnetosphere is so similar to that of the Earth.

Neptune

Although Neptune's large satellite Triton orbits at 14.6 R_N, well inside the magnetosphere, it appears that rapid transport does not allow large plasma densities to build up. Protons and N^+ ions were detected at typical densities of 0.1 cm^{-3}, reaching a few cm^{-3} very close to Neptune (Belcher et al 1989, Richardson et al 1991). Richardson et al (1991) show that variations in both density and temperature with distance are consistent with Triton being a 10^{25} ions s^{-1} source of plasma with strong inward diffusion on a time scale of a few days. The N^+ ions are thought to be produced directly in the interaction of the magnetospheric plasma with the satellite's atmosphere (Yung & Lyons 1990), while the protons come from the ionization of a large hydrogen cloud ($n \approx 300$ cm^{-3}) which extends inward from Triton's orbit to about 8 R_N (Zhang et al 1991). Inside a distance of ~ 7 R_N there appear to be significant losses, due to pitch-angle scattering which causes the ions to stream along the magnetic field into the atmosphere of Neptune or due to charge-exchange if Neptune has a dense neutral hydrogen corona (Richardson et al 1991). The difficulty with this simple picture is that several predictions of strong longitudinal asymmetries in plasma density (Broadfoot et al 1989, Hill & Dessler 1990, Richardson et al 1990, Selesnick 1990) are not observed. Moreover, the convection models of Selesnick (1990) and Hill & Dessler (1990) predict outward diffusion on the dayside of the magnetosphere whereas the data indicate inward diffusion (Richardson et al 1991). Clearly, considerable further study is required in order to understand the plasma configuration and dynamics of Neptune's magnetosphere.

ENERGETIC PARTICLE POPULATIONS

All magnetospheres have significant populations of particles with energies well above the thermal population, at keV–MeV energies (see reviews in

Dessler 1983, Gehrels & Mathews 1984, Bergstrahl et al 1991, as well as Mauk et al 1991). These particles are largely trapped by the strong planetary magnetic field in long-lived radiation belts (summarized in Table 3). Where do these energetic particles come from? Since the interplanetary medium includes energetic particles of solar and galactic origins, an obvious possibility is that these energetic particles were "captured" from the external medium. In the cases of the giant planets, the observed high fluxes are hard to explain without additional internal sources. Compositional evidence also implies that some fraction of the thermal plasma is accelerated to high energies, either by tapping the rotational energy of the planet, in the cases of Jupiter and Saturn, or by processes in the distorted magnetic field in the tail, in the cases of Earth, Uranus, and Neptune. Particle drifts in a nonuniform magnetic field lead to ions and electrons drifting in opposite directions around the planet, producing an azimuthal electric current, called a *ring current*. If the energy density of the energetic particle populations is comparable to the magnetic field energy (i.e. $\beta > 1$), then the ring current produces a magnetic field (ΔB) that significantly perturbs the planetary magnetic field. Table 3 shows that this is the case for Jupiter and Saturn, where the high particle pressures inflate and stretch out the magnetic field and generate a strong ring current in the magnetodisc. While Uranus and Neptune have significant radiation belts, the energy density remains small compared with the magnetic field (i.e. $\beta \ll 1$) and the ring current is very weak. Dessler & Parker (1959) related the

Table 3 Energetic particle characteristics

	Earth	Jupiter	Saturn	Uranus	Neptune
Phase Space Density[a] 100 MeV/G ions $c^2(cm^2 s\ sr\ MeV^3)^{-1}$	2×10^4	2×10^5	6×10^4	8×10^2	8×10^2
β[b]	<1	>1	>1	~0.1	~0.2
ΔB (nT)	10-23	200	10	<1	<0.1
$E_{Particle} / E_{Magnetic\ Field}$	$2\text{-}5 \times 10^{-4}$	3×10^{-4}	3×10^{-4}	$<3 \times 10^{-5}$	$<10^{-5}$
Auroral Power (Watts)	10^{10}	10^{14}	10^{11}	10^{11}	$<10^8$

[a] From Cheng et al (1987). Neptune value from A. F. Cheng (private communication).
[b] In the body of the magnetosphere. Higher values are often found in the tail plasma sheet and, in the case of the Earth, at times of enhanced ring current.

magnetic field produced by the ring current to the kinetic energy of the trapped particle population, scaled to the dipole magnetic energy external to the planet. Applying the Dessler-Parker relation to planetary magnetospheres we find that while the total energy content of magnetospheres varies by many orders of magnitude and the sources are very different, it appears that the particle energy builds up to only 1/1000 of the magnetic field energy in each magnetosphere. Earth, Jupiter, and Saturn all have energetic particle populations close to this limit (e.g. Connerney et al 1983). The radiation belts of Uranus and Neptune are much less than this limit, perhaps because it is harder to trap particles in nondipolar magnetic fields (Connerney et al 1991).

Where do these energetic particles go? The majority appear to diffuse inwards towards the planet. Loss processes for energetic particles in the inner magnetospheres are satellite absorption, charge exchange with neutral clouds, and scattering by waves so that the particles stream into the upper atmospheres of the planets where they can excite auroral emission and deposit large amounts of energy (e.g. Cheng et al 1987).

REMOTE SENSING OF GIANT PLANET MAGNETOSPHERES

The Voyager ultraviolet spectrometer measurements of molecular and atomic hydrogen emissions from Jupiter, Saturn, and Uranus show strong enhancements near the planet's magnetic poles. The nature of the spectra and the location of the emissions first indicate that they are auroral and, further, reveal the characteristics of the particles that are precipitating from the magnetosphere into the upper atmosphere. While it is not clear which species (electrons, protons, or heavy ions) are responsible for each component of the auroral emissions, Table 3 shows that the planets with higher radiation belt fluxes have brighter aurora. The UV emissions from Neptune are reported by Broadfoot et al (1989) and Sandel et al (1991) to be very weak with no clear auroral signature. The roles of Triton and the nondipolar magnetic field in the origin of Neptune's weak aurora are currently under debate (Sandel et al 1991, Cheng 1991a,b).

The giant planets are strong radio sources as illustrated by Figure 12 (see reviews by Zarka 1991 and Leblanc 1991). The radio sources of the Earth and Saturn are located in the auroral polar regions of both hemispheres and the beams are fixed in local time—on the nightside for the Earth and on the dayside for Saturn. For Jupiter the presence of Io and the plasma torus lead to many radio emissions. Uranus' main radio source corotates with the planet and is located on the night polar region of the planet. Among the proposed generation mechanisms the most often

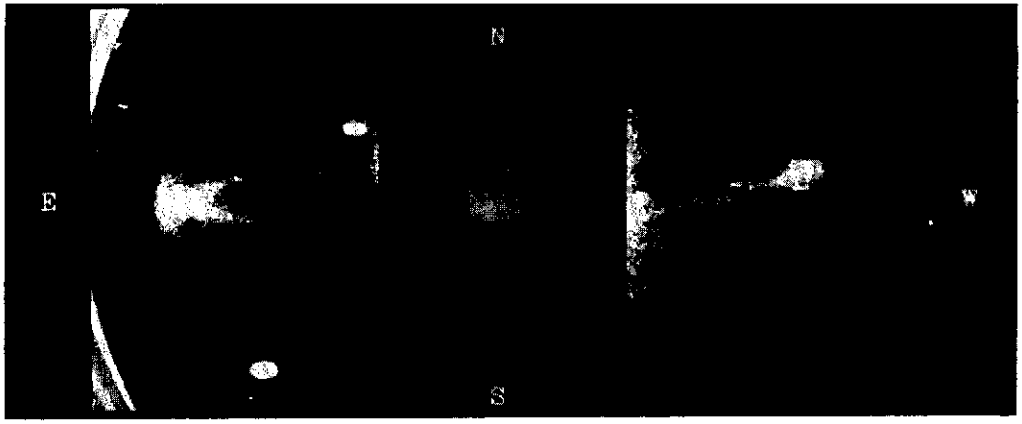


Figure 11 Image of optical emission (6731 Å) from S^+ ions in the Io plasma torus obtained on January 11, 1990 by Schneider and Trauger at the Catalina Observatory. The (circular) instrument field of view is 15 R_J wide. Io's orbital plane is horizontal. The "triptych" is a single image, but the left and right panels are enhanced differently to show detail, and Jupiter's image in the central panel is exposed through a strip of neutral density filter which transmits 10^{-4} of the light.

cited for the radio emission is the cyclotron maser instability. This mechanism predicts beaming of the emission in a narrow range of angles almost perpendicular to the magnetic field in the source region. Solar wind control of the radio emissions is very strong for Earth and Saturn but the degree of correlation of the solar wind fluctuations with Jupiter's radio emissions is much less. Again, the strength of radio emission from a planet seems to be related to the magnetospheric particle fluxes.

Flybys of the giant planets are rare. In 1996 the *Galileo* spacecraft will go into orbit around Jupiter and *Cassini* is currently scheduled to orbit Saturn in 2004. In the meantime, important observations of the magnetospheres of Jupiter and Saturn can be made from Earth (or Earth orbit in the case of X-ray and UV emissions) (Brown et al 1983, Feldman & Bagenal 1990). Figure 11 shows an image of S^+ emission from the Io torus obtained by N. Schneider and J. Trauger with a ground-based telescope. Jupiter's magnetosphere is a dynamic object. To understand its variability it is necessary to study the coupled, highly nonlinear system of the Io torus, the magnetosphere, and Jupiter's ionosphere (sketched in Figure 13). One of the aims of the International Jupiter Watch is to make synoptic measurements of emissions from the Io torus at the same time as measuring the auroral emissions at radio, infrared, ultraviolet, and X-ray wavelengths (Russell et al 1990). Although the large distances to Uranus and Neptune severely limit the emissions that can be detected from Earth, it would be

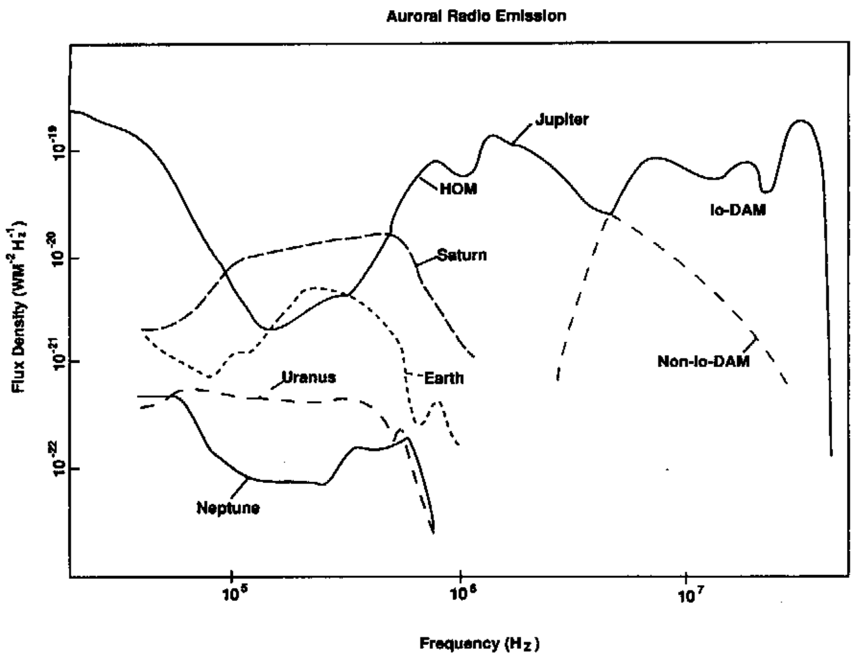


Figure 12 Averaged spectra of the auroral radio emissions computed from 2 days of Voyager Planetary Radio Astronomy data recorded from a range of 100–200 planetary radii. (Adapted from Zarka 1991.)

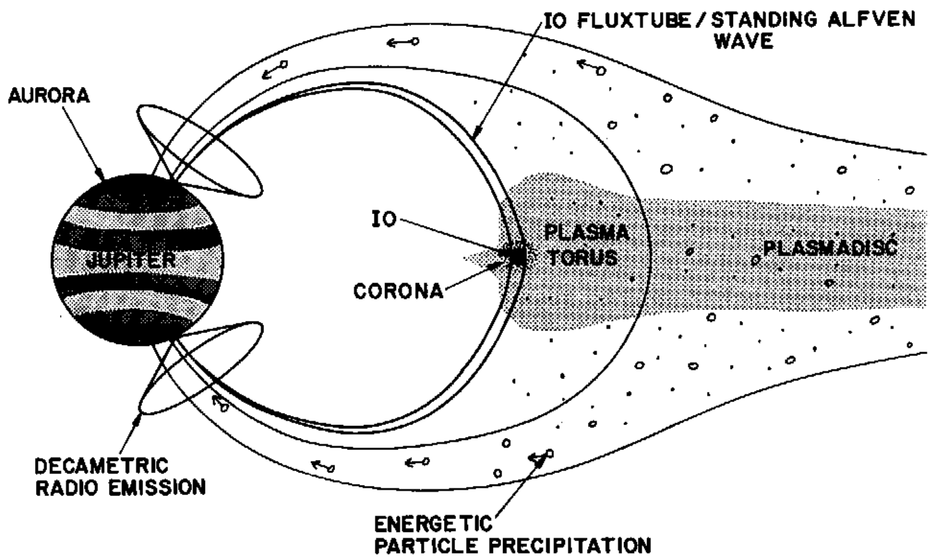


Figure 13 The connections between Io, the magnetosphere, and Jupiter's atmosphere.

valuable to send orbiting spacecraft to these irregular magnetospheres, particularly at a season when Uranus' rotation axis is pointed away from the solar wind direction to produce a configuration very different from that explored by Voyager 2 in 1986.

ACKNOWLEDGMENTS

The author is very grateful for helpful comments from Jack Connerney, Andy Cheng, Alex Dessler, Arkee Eviatar, Melissa McGrath, Ralph McNutt Jr., John Richardson, Nick Schneider, and Richard Selesnick. She acknowledges support by NASA grant NAGW 1622.

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