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OUTER PLANET MAGNETOSPHERES: A TUTORIAL

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ABSTRACT

Outer planetary magnetospheres represent giant laboratories for testing our ideas of how magnetospheres behave. In this tutorial review we examine the role of external and internal pressure in determining the size and shape of the magnetosphere. We examine the relative roles of reconnection with the solar wind magnetic field and the mass addition inside the magnetosphere in driving the circulation of plasma in the magnetosphere. We also examine how the jovian magnetosphere maintains a steady state in an average sense despite the continued addition of mass deep in the magnetosphere.

INTRODUCTION

The sun's ionized corona expands rapidly, nearly isotropically, into the surrounding heliosphere carrying the solar magnetic field with it. This expanding magnetized plasma interacts with the planets creating planetary magnetospheres, regions of enhanced magnetic field strength surrounding the planet where magnetic stresses play a dominant role in controlling the flow of the plasma. The nature of the obstacle to the solar wind flow is important in determining the nature of a planetary magnetosphere. If the planet has its own strong magnetic field due to an interior magnetic dynamo or a remanent field of a magnetized crust, then the magnetosphere is termed intrinsic. The size of an intrinsic magnetosphere is determined by the location of the point where the dynamic pressure of the solar wind flow is equal to the magnetic pressure of the intrinsic magnetic field. For Mercury this occurs just above the surface of the planet, whereas for Jupiter it occurs close to 100 times further from the center of the planet than the cloud tops. Because the solar wind flows supersonically, that is the flow is much faster than the speed of a compressional wave that could deflect the plasma flow, then a bow shock forms that slows, heats and deflects the flow before it reaches the magnetic obstacle. This shock stands off in front of the obstacle at a distance sufficiently far that the compressed solar wind plasma can flow around the obstacle.

Induced magnetospheres occur when the region of strong magnetic field arises not from magnetism within the planetary obstacle but from the interaction of the solar wind with the obstacle. Induced magnetospheres in turn can be divided into two classes, one in which the planetary body is adding mass to the solar wind flow in the form of ions newly created from a neutral atmosphere. This occurs most spectacularly at comets and less so at Venus and Mars and also at the moons Io and Titan where a "magnetosphere" is created by a flowing planetary wind. The other class of induced magnetospheres arises from classical electromagnetic induction in a highly electrically conducting medium. This conductor can be the electrically conducting interior of a planet or moon such as an iron core or a salt-water ocean, such as in Europa, or it can be the ionosphere of a planet above the surface, such as at Venus and Mars. In these cases the magnetic field external to the planetary body is excluded from the interior of the conductor for a length of time dependent on the size and electrical conductivity of the obstacle. This time can be long compared to the time scale of directional changes in the exterior magnetic field. Currents flow in the conductor to oppose the field change and the field outside obstacle increases, creating a magnetic barrier that in turn deflects the flowing plasma. As in the case of intrinsic magnetospheres, either class of induced magnetospheres can lead to the formation of a bow shock, standing in front of the obstacle when the flow velocity exceeds the velocity of the compressional wave that is required to deflect the flow around the obstacle.

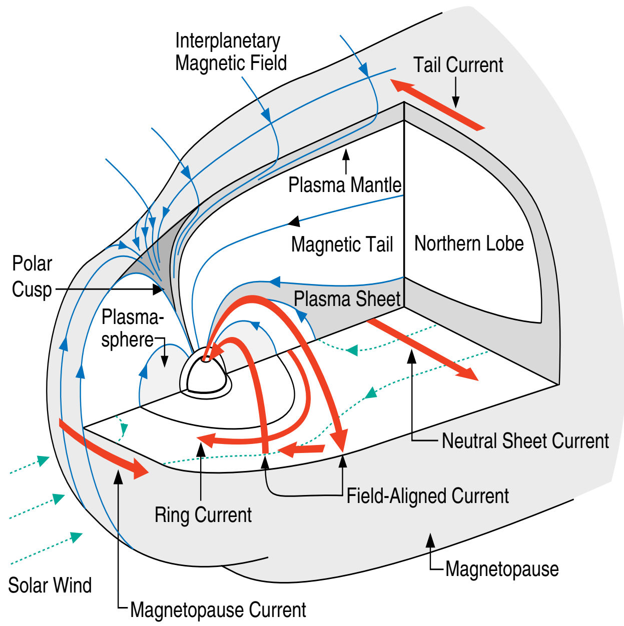


Fig. 1. Cut away model of the terrestrial magnetosphere showing the plasma regions, magnetic field lines, electric currents and flows.

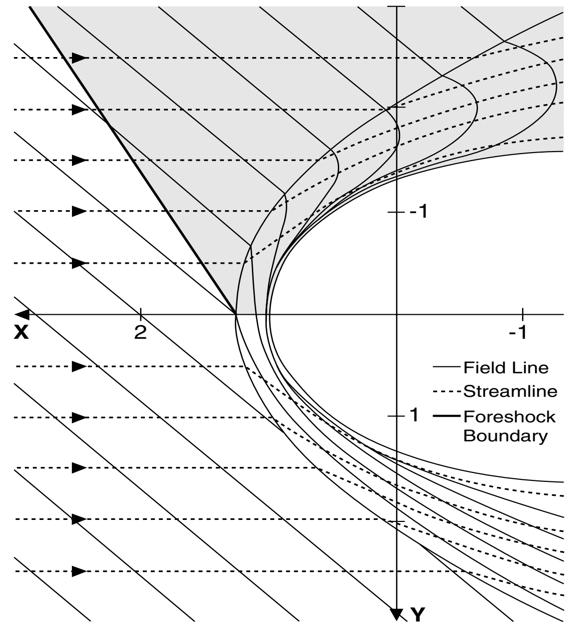


Fig. 2. Magnetic field lines and flows in the plane containing the upstream field and flow passing through the stagnation point as calculated in the convected field gas dynamic model of the interaction of the solar wind with the Earth's magnetosphere (after Spreiter et al., 1966).

Herein we examine the physics of the outer planet magnetospheres. We have visited the magnetospheres of Jupiter and Saturn many times but those of Uranus and Neptune only once. These magnetospheres are all intrinsic. No spacecraft has yet visited Pluto, but unless the atmosphere and interior are completely frozen we would expect one of the classes of magnetospheres to form.

Above we discussed briefly the size of intrinsic planetary magnetospheres as determined by a balance of pressures, between the dynamic pressure of the flowing solar wind and the magnetic pressure of the intrinsic magnetic field. Figure 1 shows an intrinsic magnetosphere as deduced from observations of the terrestrial magnetosphere. The magnetosphere forms a cavity in the flowing solar wind and throughout much of this cavity the pressure is dominated by the magnetic field. The pressure that determines the size of the cavity is normal to the surface of the cavity. Outside the cavity is plasma whose pressure decreases from outside to inside across the cavity boundary. This pressure gradient exerts an inward force. It is balanced by a magnetic pressure force pushing outward as the magnetic field increases from outside to inside across the cavity boundary, or magnetopause. The relationship between this normal component of the pressure and the directed dynamic pressure in the upstream solar wind is complex and is only understood semi-empirically (e.g. Petrinec and Russell, 1997). Similarly, the magnetic field depends on a multitude of currents, not just those interior to the planet. Thus the point of pressure equilibrium or force balance can move. Since the magnetic flux crossing the surface of the planet is fixed on the time scale of most magnetospheric "events", any variations in the magnetopause location under conditions of constant external pressure must involve a change in shape of the magnetosphere. Rapidly rotating magnetospheres with strong internal sources of plasma add an additional complexity that will be discussed below.

The magnetosphere illustrated in Figure 1 is stretched in the antisolar direction. This magnetotail, as it is called, is a region in which energy can be stored, analogous to the energy that can be stored in an electrical circuit by an inductor. However, to understand the behavior of the magnetosphere one has to understand the transport of mass and magnetic flux that occur on time scales much slower than the speed of light. Thus one can often catch a magnetosphere in the act of changing, or in a metastable state, ready to change.

One can add energy to this system by simply compressing it, just as one can store energy in a compressed spring. The work done, or energy stored, is the force times the distance moved normal to the surface, integrated over the magnetosphere. One can also add energy to the system by eroding the magnetic field on the dayside and

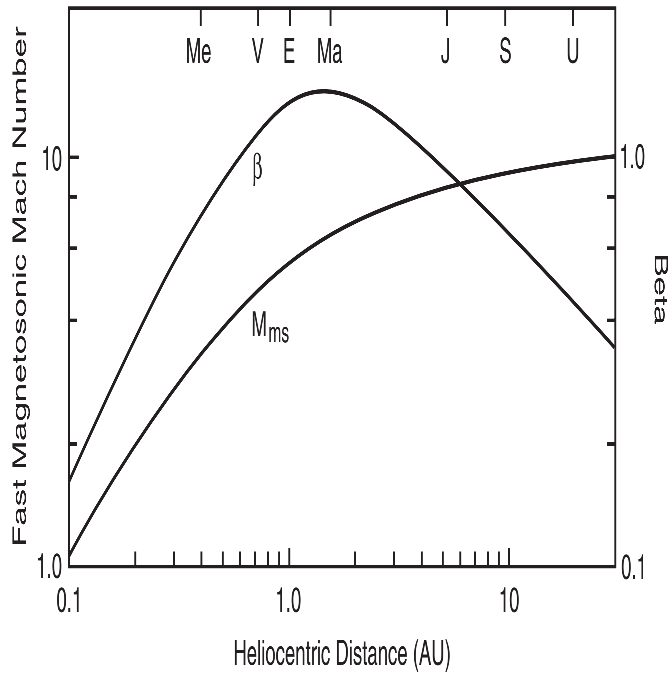


Fig. 3. Expected heliocentric variation of the fast magnetosonic Mach number of the solar wind flow relative to the planets and the solar wind beta or ratio of the magnetic to thermal pressure (after Russell et al., 1982).

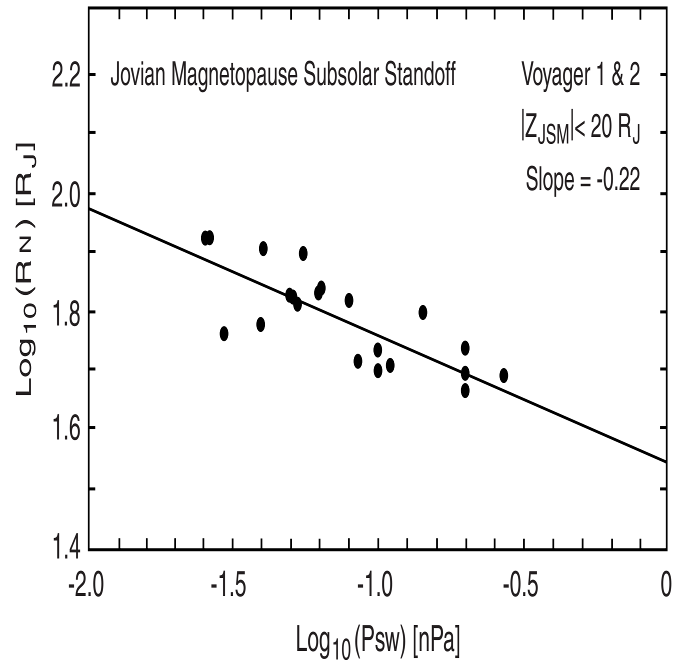


Fig. 4. The location of the magnetopause nose plotted versus the solar wind dynamic pressure for Voyager 1 and 2 data. The line gives the best fit to the data on a log-log scale (after Huddleston et al., 1998a).

carrying it into the tail. This requires a tangential stress such as friction at the surface of the magnetosphere. This tangential stress can be a viscous interaction associated with waves on the boundary in the presence of dissipation, with particles being scattered from the flowing, shocked solar-wind plasma into the magnetosphere, or by magnetic coupling of the magnetospheric and solar wind magnetic field. This coupling is illustrated in Figure 1 above the magnetosphere and behind the depression in the shape of the magnetopause called the polar cusp. Here the magnetic field lines are bent in the direction as to slow the solar wind flow. As the solar wind slows in this region, mechanical energy is removed from the flow, and is stored in the tail lobes where the magnetic field energy increases. The transport of energy into the tail occurs through an electromagnetic Poynting flux.

Magnetospheres are vast in scale but contain very little total mass. The stress applied to the magnetosphere by the solar wind must be ultimately taken up by the planet. One of the ways to transmit this stress to the ionosphere and thence through collisions to the upper atmosphere and the planet, is through currents parallel to the magnetic field as illustrated in Figure 1. These currents close on pressure gradients in the magnetosphere. Another is through the gradient in the Chapman-Ferraro currents acting on the planet's dipole (Siscoe, 1966). This latter process is most important on planets such as Mercury where closure currents at the feet of field lines may be inhibited.

Obviously it is very important to understand the effective viscosity of the solar wind flow past the magnetopause. This viscosity depends on many factors. Waves set up on the magnetopause by the non-steady interaction of the solar wind could act to drag on the magnetospheric plasma if the magnetosphere dissipated the waves set up on the magnetospheric side of the boundary. Similarly the conditions in the plasma exterior to the magnetopause, the magnetosheath, also affect the viscosity, especially if it occurs through the coupling of magnetic fields across the boundary through the process that is called magnetic reconnection.

Figure 2 illustrates the flow of plasma from the solar wind, through the bow shock, into the magnetosheath and around the magnetopause. The magnetic field (solid lines) and flow (dashed lines) are drawn in the plane that contains the upstream magnetic field and cuts through the stagnation point at the subsolar-wind point. The shaded region shows an area of the solar wind where energetic ions have been created, either reflected from the shock or leaking from the region behind the shock. These particles stream back into the solar wind leading to additional unsteadiness in the interaction on that side (generally the dawn side) of the magnetosphere. Behind the shock the plasma is slowed, compressed, heated and deflected, only to later expand as it moves behind the magnetosphere.

We know how much slowing, compression, heating and deflection occurs via the Rankine-Hugoniot equations, a combination of fluid equations of motion and Maxwell's electromagnetic equations as applied to thin planar boundaries. These equations tell us that the strength of the bow shock is controlled by the speed of the fast mode compressional wave relative to the solar wind velocity. This ratio, called the Mach number, is greater than one when the solar wind velocity normal to the shock front exceeds the fast mode speed upstream at the shock. The greater is this ratio the hotter the plasma downstream becomes until the thermal pressure reaches the upstream dynamic pressure. Since the magnetopause is a region of pressure balance along the normal to the boundary, this increase in temperature with Mach number decreases the density (and the magnetic field) just exterior to the magnetopause (Le and Russell, 1994). This weakening of the potential magnetic stress at the magnetopause appears also to weaken the coupling of the solar wind to the Earth's magnetosphere (Scurry and Russell, 1991). For the purposes of this review of outer planet magnetospheres, we show in Figure 3 how we expect the Mach number of the solar wind flow relative to the planets to vary with heliocentric distance. We also show the expected variation of the beta value of the solar wind with distance, the ratio of magnetic to thermal pressure. This affects processes in the solar wind but not so much reconnection at the outer planets because the beta value in the magnetosheath is dominated by the large Mach number of the preshock solar wind flow. The expected strength of the outer planet bow shocks is confirmed by their large overshoots in magnetic field strength, much exceeding overshoots seen in the strongest terrestrial bow shocks (Russell et al., 1982). Thus we expect that magnetic reconnection with the solar wind may play a much lesser role at the outer planets than at Mercury and the Earth even in the absence of the other factors that we discuss below.

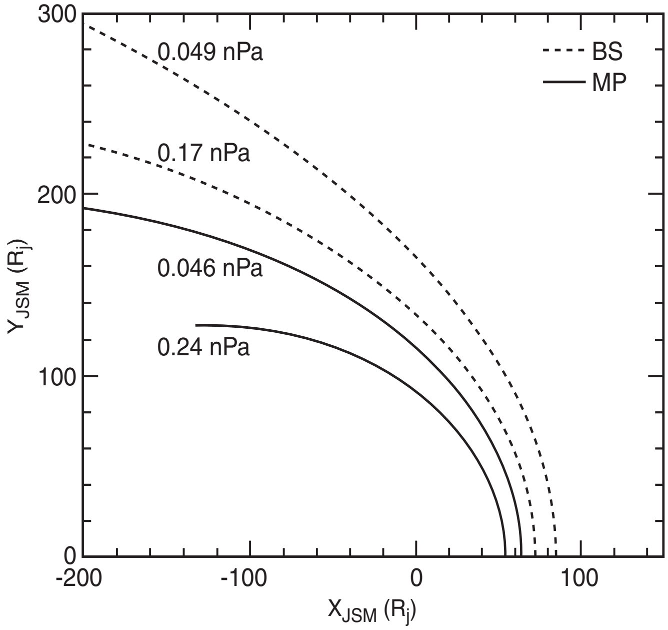
THE SIZE OF PLANETARY MAGNETOSPHERES

We have sufficient observations of the size of the magnetospheres of Earth, Jupiter and Saturn to compare carefully with theoretical expectations and enough observations of the magnetospheres of Mercury, Uranus and Neptune to do a first order check for closeness of fit. Table 1 lists the typical dynamic pressure expected at each of these planets, their magnetic moments, the expected distance from the planetary center to the subsolar wind magnetopause and the observed distance to this point. Also listed in the right-hand columns are two parameters that are relevant to the importance of reconnection in determining the importance of "reconnection" in driving the flows within the magnetosphere. We discuss these columns later.

Table 1. Factors Affecting the Magnetopause

Planet	R [AU]	Dynamic Pres [Pa]	MagMom [Tm^3]	Rexp [km]	Robs [km]	Mms	Dp
Mercury	0.39	5.9×10^{-9}	4.0×10^{12}	4.3×10^{3}	3.7×10^{3}	3	85
Earth	1.0	2.3×10^{-9}	8.0×10^{15}	6.3×10^{4}	6.3×10^{4}	5.5	700
Jupiter	5.2	8.4×10^{-11}	1.6×10^{20}	30×10^{5}	40×10^{5}	8	5811
Saturn	9.9	2.3×10^{-11}	4.6×10^{18}	12×10^{5}	12×10^{5}	10	1218
Uranus	19.2	6.1×10^{-11}	3.9×10^{17}	6.9×10^{5}	6.4×10^{5}	10.5	338
Neptune	30.1	2.5×10^{-12}	2.2×10^{17}	6.3×10^{5}	6.5×10^{5}	11.0	210

Mercury, Uranus and Neptune all have magnetospheres of approximately the expected size. We do not know the actual solar wind conditions when the magnetopause was encountered for these bodies, nor do we have sufficient observations to average over solar wind variability, but we can say there are no surprising differences between our expectations and observations. Earth, Jupiter and Saturn all have multiple spacecraft observations over many years and varying solar wind conditions. The observed sizes of the magnetospheres agree well with expectations except for Jupiter that appears to be a factor of 33% too large. Since the magnetic field pressure falls off as the sixth power of the distance, this discrepancy would correspond to an error in the magnetic moment of Jupiter of greater than a factor of 5, if the magnetospheric pressure were solely magnetic, an error highly unlikely because of the multiple measurements of the jovian field over many years. The cause of the discrepancy is the presence of an additional component of the internal magnetospheric pressure that has increased the pressure by a factor of 2.4.



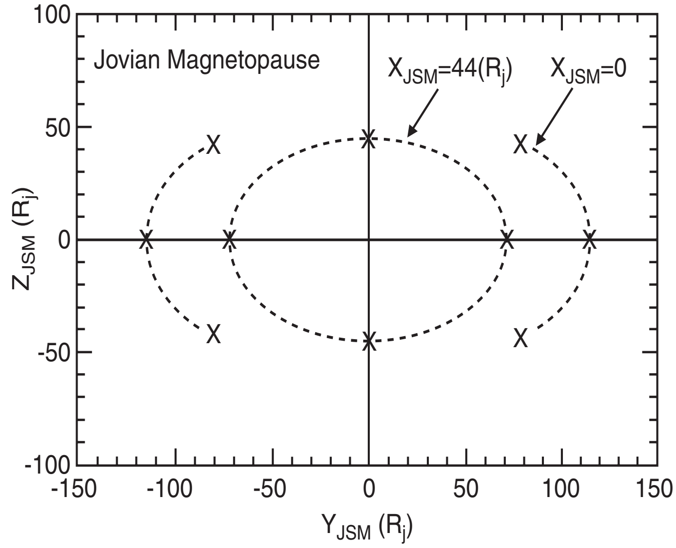


Fig. 5. The location of fitted jovian magnetopause (solid) and bow shock (dashed) locations for two solar wind pressures. Only data near the equatorial regions have been used (after Huddleston et al., 1998a).

Fig. 6. Magnetopause cross sections in front of the dawn-dusk meridian and in the dawn-dusk meridian for constant solar wind pressure (after Huddleston et al., 1998a).

Figure 4 gives us some insight into the nature of this additional component of pressure. It shows the location of the jovian magnetopause as a function of the observed solar wind dynamic pressure (Huddleston et al., 1998a). If the interior pressure were solely due to the intrinsic magnetic field the slope of the variation with dynamic pressure would be 0.17. The observed dependence is a more sensitive function of the solar wind dynamic pressure as if the pressure gradient in the magnetosphere had been lessened by the presence of plasma so that a smaller exterior pressure change was able to move the magnetopause a greater distance. While Figure 4 just shows the extrapolated subsolar magnetopause distance, Figure 5 shows us this location over a range of angles away from the subsolar point, for two different solar wind dynamic pressures. Also shown are the corresponding bow shock locations (Huddleston et al., 1998a). Perhaps surprisingly the bow shock is closer to Jupiter than expected based on the terrestrial bow shock analogy. Further evidence as to the cause of the surprising close-in bow shock location is given in Figure 6 that shows the cross section of the magnetopause at 44 jovian radii from the dawn-dusk terminator and on the dawn-dusk terminator. The magnetosphere is not approximately circular in cross section but quite oval with the magnetopause stretched in the equatorial plane. There is a very simple explanation for the combined high compressibility of the magnetosphere and its odd shape and (consequent) close-in bow shock location. The moon Io provides a strong source of plasma deep in the jovian magnetosphere. This plasma is accelerated to near co-rotational speeds in the magnetosphere resulting in a strong outward centrifugal force that stretches the magnetosphere in the equatorial plane, making the magnetosphere more streamlined.

The scatter about the best-fit line in Figure 4 suggests that the location of the jovian magnetopause is quite variable. Recent Galileo studies (Joy et al., 2002) confirm this variability as shown in Figure 7. Here the cumulative probability that the nose of the magnetopause and shock lie beyond some distance has been calculated from six years of Galileo observations. These curves are then differentiated to get the probability that the bow shock and magnetopause lie at any one location, and are displayed in the bottom panel. Let us consider first the magnetopause on the lower right. The largest peak corresponds to an average distended magnetopause as we discussed above but there is a second peak, smaller in size but more distended, almost 50% further out, corresponding to a solar wind pressure a factor of 3 less or a magnetospheric pressure a factor of three more. Even more surprising is the null in occurrence between the peaks. Either the magnetosphere or the solar wind has two distinct pressure states. Returning to the lower left-hand panel illustrating the distribution of bow shock locations, we see a repeat of the same behavior. The relative size of the two peaks is similar, and their relative distances are again about 50%. Here

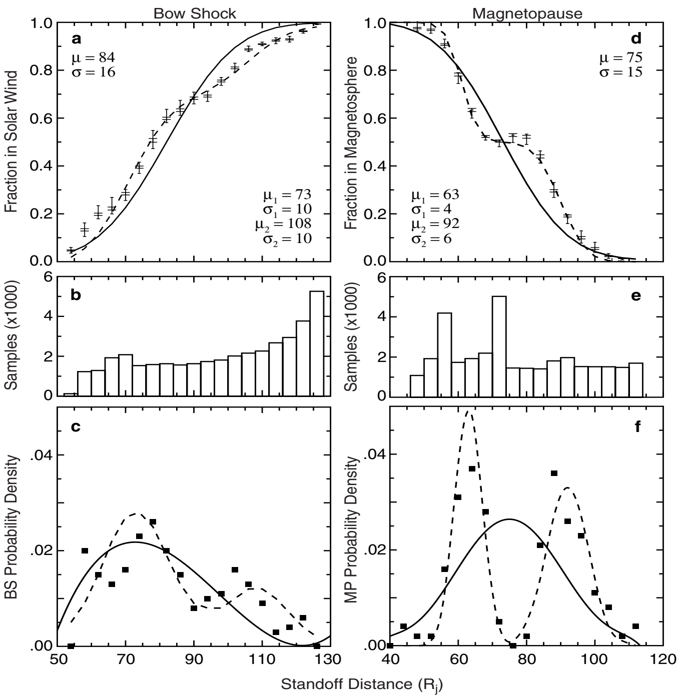


Fig. 7. Location of the jovian magnetopause and bow shock as observed by Galileo. Data have not been adjusted to constant solar wind pressure. Top panels show cumulative probabilities. Middle panels show the amount of data examined in minutes. Close to two years of data have been used in the vicinity of the bow shock and over one-year near the magnetopause. The remainder of the time the spacecraft was either closer to the planet, or more distant, or no data were received on Earth (after Joy et al., 2002).

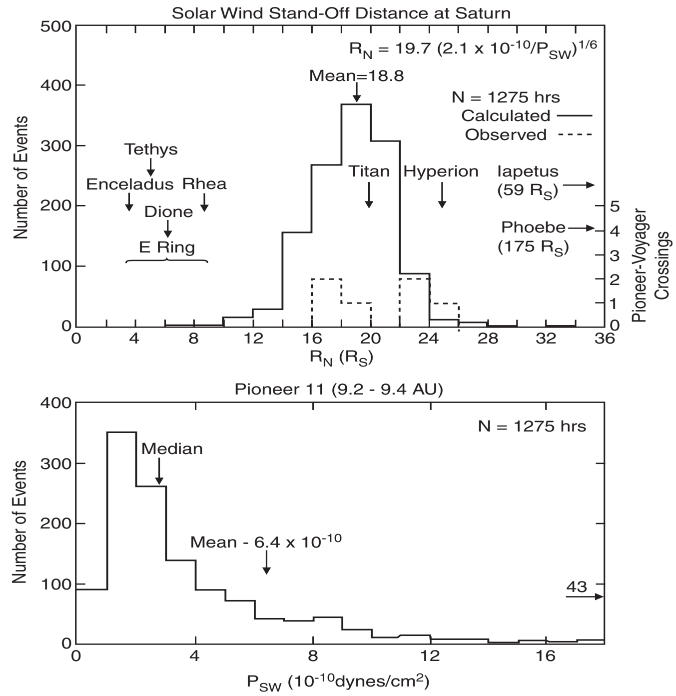


Fig. 8. Magnetopause location at Saturn and typical solar wind pressures at Saturn (after Slavin et al., 1985).

the minimum between the two peaks does not reach zero but we would not expect it to do so because the variability of solar wind Mach number at constant dynamic pressure would give a broad distribution of bow shock locations for constant magnetospheric size because the degree of compression of the magnetosheath plasma varies with Mach number. The relative locations of the two sets of bow shock and magnetopause peaks (inner and outer) both are about 1.15 indicating that they do both correspond and that the shape of the magnetosphere is about the same in both instances.

If the solar wind were responsible for the pressure variation the peaks would maintain their relative positions as discussed by Joy et al. (2002). However, this interpretation requires the existence of two states of the solar wind pressure with rather narrow spreads in pressure around the average of these two states. The distribution of pressure in the outer solar system has been studied by Slavin et al. (1985) near both Jupiter and Saturn and is shown in Figure 8 for Saturn. There is only one peak with a high pressure tail on the distribution. The solar wind appears not to be the cause of the bimodal size of the jovian magnetosphere. We must conclude that the jovian magnetosphere has two states: a distended mass-loaded one and a more mass-loaded, more distended one. As we see below reconnection events in the tail provide a convenient means to transition from the fully mass-loaded to the partially mass-loaded state. Why the fully mass-loaded state is relatively rare and why intermediate states seem not to be populated are not immediately apparent.

Figure 8 also shows us a plot of the location of the observed Saturn magnetopause (dashed lines). It too is bimodal. The separation in peaks is only 33% but the uncertainty the location of these peaks from only 6 magnetopause crossings is too great to make any comparison with the jovian case. This is a study for the Cassini epoch.

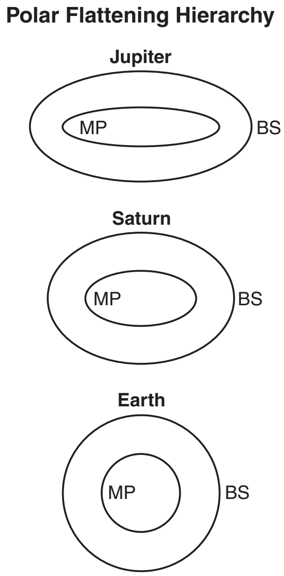


Fig. 9. The more circular cross section of the terrestrial magnetosphere produces a more circular bow shock cross section but one which is further away from the magnetopause (after Slavin et al., 1985).

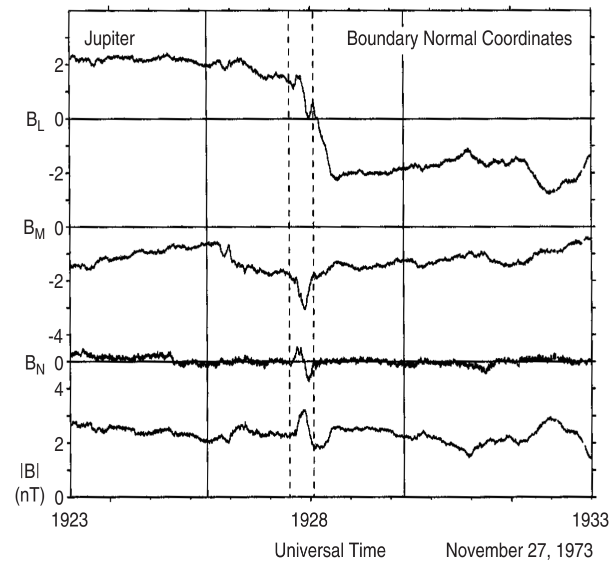


Fig. 10. Flux transfer events at Jupiter as seen in the Pioneer 10 magnetic field data during the magnetopause crossing. Magnetic fields have been rotated into boundary normal coordinates with N along the magnetopause normal (after Walker and Russell, 1985).

We are now ready to address the question of why the separation of the bow shock and the magnetopause appears to be about half that at Earth. Figure 9 illustrates why this occurs. For Earth (bottom panel) the magnetopause is nearly circular in cross section and the obstacle is blunt. For Jupiter the centrifugal force makes the magnetosphere bulge in the equatorial region, creating a more streamlined obstacle and allowing the flow to move by the planetary magnetosphere more rapidly and hence with less buildup over the front of the obstacle. Figure 9 does not illustrate one aspect of the interaction. The bow shock is closest to the magnetopause near the subsolar point. The bow shock always is more circular in cross section than the magnetopause because the characteristics from any point on the magnetopause spread to an arc on the bow shock.

RECONNECTION

The process known as reconnection (Dungey, 1961) leads to the connection of the terrestrial and solar wind magnetic fields. This has long been postulated as the ultimate cause of the geomagnetic storm, substorms and the circulation of plasma in the terrestrial magnetosphere. It occurs on the dayside of the terrestrial magnetosphere when the solar wind magnetic field is southward, opposite that of the terrestrial magnetic field at the subsolar point. It accelerates the plasma in the direction of the magnetic stress as expected from theory (Paschmann et al., 1979) and the process may be quasi-stationary (Sonnerup et al., 1981) or time-varying (Russell and Elphic, 1978). Spatially limited time-varying reconnection results in a phenomenon that has been termed a flux-transfer event. In a flux transfer event a bipolar magnetic field signature appears in the direction along the magnetopause normal and a strengthened field tangential to the boundary as a flux rope slides along the magnetopause. Such flux transfer events are observed frequently at Earth and Mercury (Russell and Elphic, 1978; Russell and Walker, 1985) and perhaps less often at Jupiter (Walker and Russell, 1985). Figure 10 shows an example of a jovian flux transfer event. It looks very much like a weak terrestrial flux transfer event.

Very few magnetopause data are available at the magnetopause crossings of the outer planets, Saturn, Uranus and Neptune, but the data that are available do suggest that reconnection occurs. Figures 11 and 12 show the magnetic field upon crossing the uranian and neptunian magnetopauses (Huddleston et al., 1997). The normal component is transiently large and unidirectional. This is a rare signature in terrestrial flux transfer events but does signify that reconnection has occurred. Thus, while the style of reconnection may vary across the solar system, its occurrence seems to be ubiquitous.

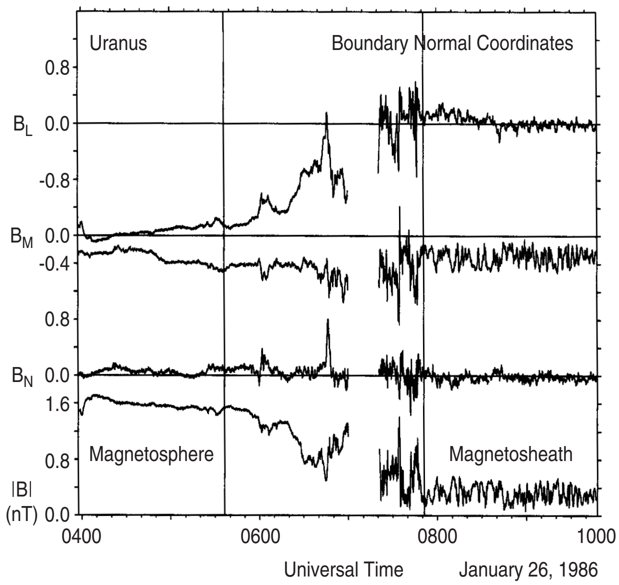


Fig. 11. Magnetic field measurements obtained while Voyager 2 was crossing the magnetopause of Uranus, displayed in boundary normal coordinates (after Huddleston et al., 1997).

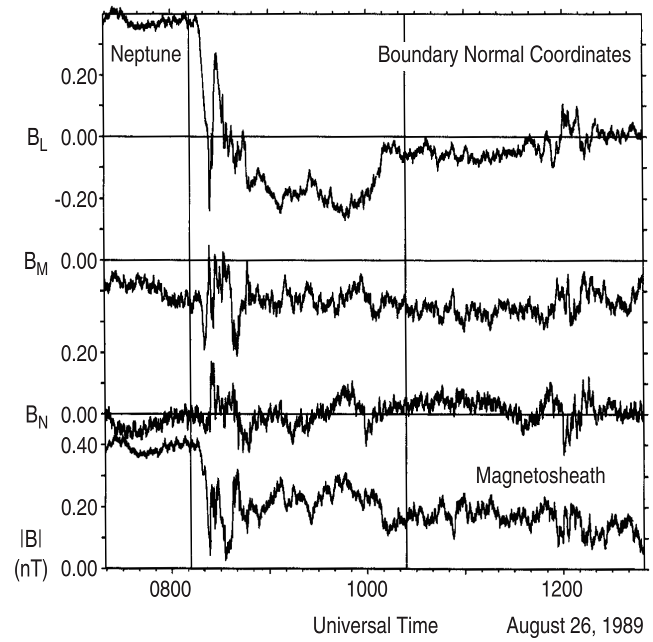


Fig. 12. Magnetic field measurements obtained while Voyager 2 was crossing the magnetopause of Neptune, displayed in boundary normal coordinates (after Huddleston et al., 1997).

The presence of reconnection at the terrestrial magnetopause is critical to the energization of magnetospheric processes. It is not obvious, however, that it should be as important in energizing the magnetospheres of the outer solar system. As mentioned above, high solar wind Mach numbers mitigate against reconnection. Table 1 shows in its second column from the right the typical Mach number at each of the intrinsic magnetospheres. The Mach number in the outer solar system is about twice the value in the inner solar system and hence we expect that magnetopause reconnection would be weaker in the outer solar system.

A second argument for diminished efficiency of reconnection is given in the right-most column that gives the size of the magnetospheric standoff distance measured in terms of the ion inertial length. For the plasma conditions present at the planets this is basically the ion gyro radius. The success of this parameter in ordering the nature of physical processings in magnetospheres of different size (Omidi et al., 2003) is recognition of the importance of the ratio of the radius of curvature of the obstacle relative to the ion scale in controlling these processes. This value is large for all planets, thus justifying the frequent use a fluid approximation, such as a magnetohydrodynamic simulation, to treat large-scale processes at all the planets. However, this ratio does vary by an order of magnitude from Mercury to Jupiter. Since reconnection is a kinetic and not a fluid phenomenon, all else being equal we would expect reconnection to be most important at Mercury, Neptune and Uranus and least important at Jupiter. Simply put, the size of the region on the magnetopause in which kinetic effects take place (the neutral point) is much smaller at Jupiter relative to the dimension of the system than at the other planets, as a result of the large radius of curvature of the jovian magnetosphere.

For Jupiter and possibly for Saturn there is a third reason why we would not expect magnetopause reconnection to be important. There is a much more effective engine for driving plasma circulation in these two magnetospheres and for energizing the magnetosphere. It is the same process, centrifugally driven flow, that is responsible for stretching the equatorial dimension of the jovian magnetosphere.

CENTRIFUGAL FORCE

A body continues to move in a straight line unless acted upon by an outside force. For an orbiting body that moves in a circle that outside force is gravity accelerating the body transverse to its motion so that resultant trajectory is a circle. Gravity is supplying a centripetal force that bends the trajectory and just the right energy of motion produces a circle. Ionospheres are coupled to planetary atmospheres and thence to the rotating planet and tend to rotate with the planet. The ionospheres in turn couple to the magnetosphere and causes the charged particles there to attempt to rotate with the ionosphere. At distances inside synchronous orbit where particle would orbit the planet with the period less than that of the rotation of the planet, the inward force of gravity is too great for a corotating particle to remain in orbit so that an additional force (provided generally by the magnetic field) is required to support the particle. At distances outside synchronous orbit the inward force of gravity is too weak for a corotating particle to remain in a corotating trajectory so an additional inward force is needed, again generally provided by the magnetic field.

Visualizing the behavior of particles in a rotating system is complicated if one does not move into the frame of reference of the rotating system. In the rotating frame it is common to refer to an apparent outward force called the centrifugal force that in equilibrium "balances" the inward force. In this section we adopt this approach, working in the rotating system and discussing the outward centrifugal force that is "in balance" with the inward centripetal force, the net force due to gravity and magnetic and plasma pressures.

Table 2. Factors Affecting Centrifugally Driven Circulation

Planet	Rp [km]	Ω [rads/s]	Gsurf [ms^{-2}]	Rsynch/ Rplanet	Plasma Sources
Mercury	2440	1.24×10^{-6}	3.3	96	None
Earth	6371	7.29×10^{-5}	9.8	6.6	Ionosphere
Jupiter	70000	1.77×10^{-4}	25.6	2.3	Io
Saturn	60000	1.71×10^{-4}	10.8	1.8	Rings, Moons
Uranus	25500	1.01×10^{-4}	8.6	3.2	Moons
Neptune	24830	1.01×10^{-4}	10.1	3.4	Moons

In general we do not consider centrifugal force when treating the Earth's magnetosphere even though the plasmasphere corotates with the Earth and is dense, relative to the outer magnetosphere. The reason we do not can be seen from Table 2 that shows the dimensions of the planet, the rotation rate, the surface gravitational force, the distance to geosynchronous orbit and the available plasma sources. On Earth gravitational forces and corotating centrifugal force balance at 6.6 R_E. Here the plasma is not very dense in general and even if the plasma from 6.6 R_E to the magnetopause were accelerated to corotational velocities the magnetic forces would easily balance the centrifugal force. At slowly rotating Mercury, the synchronous distance, at which a body would remain over the same location is 96 Mercury radii, far outside the magnetosphere.

Jupiter is at the other extreme. Synchronous orbit is at 2.3 jovian radii. There is a mass-loading body, the moon Io, at 5.9 jovian radii that adds a ton a second of plasma to the magnetosphere. The centrifugal force of corotating plasma at Io far exceeds the gravitational force at this point (and beyond) so that only the magnetic forces are available to confine the plasma. If the equatorial magnetic field cannot contain the plasma, the field will become more and more distorted. If the feet of the field lines cannot be frozen into the ionosphere they will slip. In either case the plasma will circulate in response to the mass-loading process. At a rate of a ton per second it does not take long (of the order of months) to build up the plasma density at Io to the value observed and a value that forces the plasma to convect outward.

Synchronous orbit is similarly close to the planet at Saturn, Uranus and Neptune. However, Uranus and Neptune do not have obvious strong plasma sources within the magnetosphere. Saturn has a strong icy ring system extending well beyond synchronous orbit so that it can provide mass that could promote centrifugally driven circulation. Moreover, at great distances, ~20 Rs, there is Titan, the moon with the greatest atmosphere of any in the solar system. However, here the magnetic field is very weak and the interaction between the mass-loaded plasma and the magnetosphere may be much different than at Io.

Figure 13 illustrates how the magnetospheric flux tubes couple to the ionosphere and ultimately to the planetary ionosphere. At high altitudes a set of magnetic field lines are pushed by the plasma, so that they are sheared with respect to the surrounding flux tubes. When the magnetic field lines are sheared, a field-aligned current arises. This current closes in the resistive ionosphere and causes a Lorentz or **J**x**B** force that drags on the ionosphere. At the top of the flux tube in the magnetosphere the currents also close across field lines flowing (radially in the case of Jupiter) on pressure gradient surfaces orthogonal to the pressure gradient force.

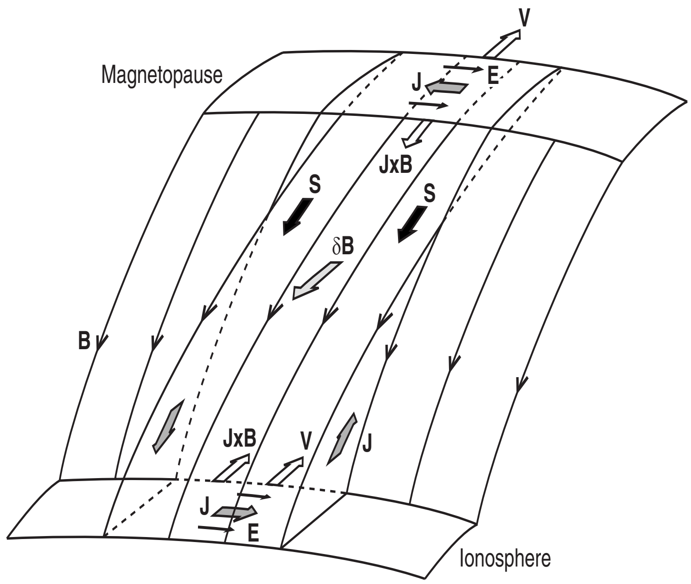


Fig. 13. The transmission of stress between the ionosphere and magnetosphere. Stresses in either the magnetosphere or ionosphere can be transmitted between the regions by shearing a flux tube with respect to its neighbors. Currents close in the ionosphere across magnetic field lines and couple the tube to the ionosphere plasma. Currents close in the magnetosphere via pressure gradient drift currents. Currents join the two regions along the magnetic field (after Strangeway et al., 2000).

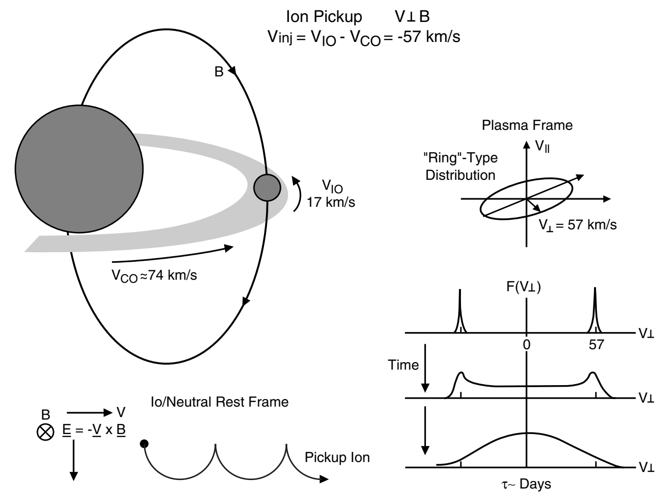


Fig. 14. Schematic of the mass loading or ion pickup process at Io. The inset lower left shows the motion in Io's frame due to the jovian corotational electric field. The right hand panel shows the behavior of the ions in velocity space as they isotropize and give up energy to ion cyclotron waves (after Huddleston et al., 1998b).

Figure 14 shows the situation at Io where the moon orbits at 17 km/s and the torus plasma rotates at 74 km/s. The upper atmosphere of Io becomes ionized and is accelerated by the electric field associated with the corotating plasma. On a kinetic level the newly added ions form a ring in velocity space that has free energy that can be released as ion cyclotron waves oscillating at the gyro frequency of the newly created ion. The ion cyclotron wave transfers some energy from perpendicular to along the field and helps the isotropize the plasma. Figure 15 shows a cut through the mass-loading region around Io by the Galileo spacecraft showing both the effect of the interaction on the fluid parameters, ion temperature, bulk velocity and magnetic field as well as the measured torus density of SO_2^+, the inferred pickup density of SO_2 and the ion cyclotron wave amplitude (Huddleston et al., 1999).

CIRCULATION OF PLASMA

It is clear from the disk-like shape of the jovian magnetosphere that the equatorial regions have been mass-loaded and it is clear from the in situ measurements at Io that the mass-loading is occurring there as ions are picked up from the upper atmosphere by the corotating torus. We even understand how this plasma is forced to corotate by the coupling to the ionosphere but we have not yet examined how mass loading supplants the terrestrial dayside reconnection process as the driver of convection. Such a plasma circulation model was proposed by Vasyliunas (1983) and shown in Figure 16. In the inner magnetosphere plasma circulates around the planet in closed drift paths. Outside of some radius the drift paths are not closed. The flux tube length stretches and the magnetic field lines pinch off to form magnetic bubbles. The bubbles move down tail and the short part of the flux tube snaps back to join the nearly corotating flow. This model is similar to Dungey's (1961) model for the Earth's magnetosphere converted to the jovian situation where it is powered by an internal source and not by the solar wind.

The Dungey model was proposed as a steady state model to explain the time-stationary circulation of the plasma. Similarly, the Vasyliunas model is a time-stationary model. However, in both magnetospheres very interesting behavior occurs as a result of temporal changes in this circulation pattern. Thus we will spend some time examining the how the circulation is powered and it becomes a time-varying system even though it may be uniformly driven.

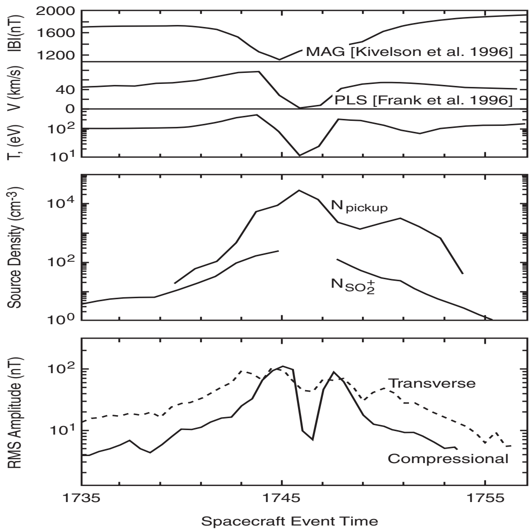


Fig. 15. Plasma and wave parameters measured along the Galileo trajectory as it passed Io on December 7, 1995 (Huddleston et al., 1999). Plasma data are from Frank et al., (1996), magnetic field from Kivelson et al., (1996).

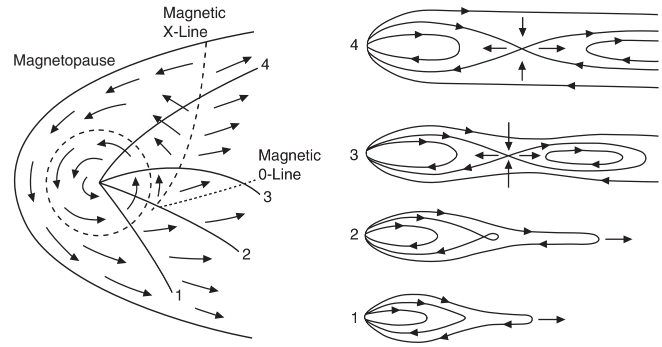


Fig. 16. Jovian magnetospheric circulation model of Vasyliunas (1983). In steady state part of the circulating plasma stretches tailward and reconnects forming an island that is ejected down the tail.

Figure 17 shows isodensity contours of the Io torus derived by Bagenal (1994). The top of the figure shows the integrated density roughly along magnetic shells and over 2π radians. If one ton per second is being added to this plasma torus, a similar amount must be lost in steady state to maintain a constant density. It is difficult to lose plasma along magnetic field lines due to the centrifugal force confining the plasma to the equatorial regions and because the wave levels are too low to scatter the ions out of this potential well (Russell et al., 2001a). To maintain steady state the plasma must move outward at the velocities given along the top of the figure. At 9 m/s it takes the plasma 3 months to move 1 jovian radius, but out further it requires only one month (at 31 m/s) or two weeks (at 68 km/s). Even in the region from 8 to 9 R_J, the plasma circulates Jupiter about 30 times as it moves radially one jovian radius.

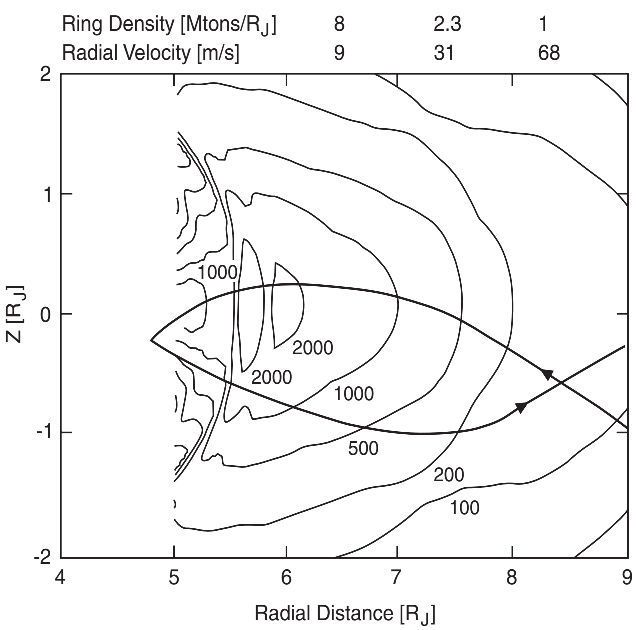


Fig. 17. Isodensity contours of the Io torus (after Bagenal, 1994).

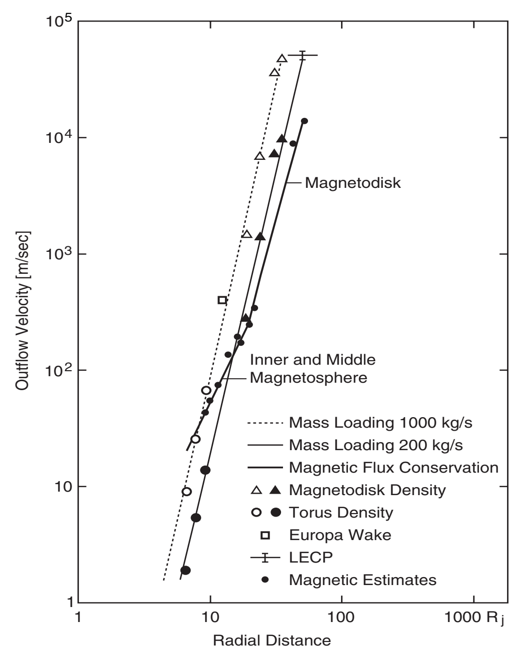


Fig. 18. Estimates of the radial outflow velocity due to a variety of techniques (Russell, 2001).

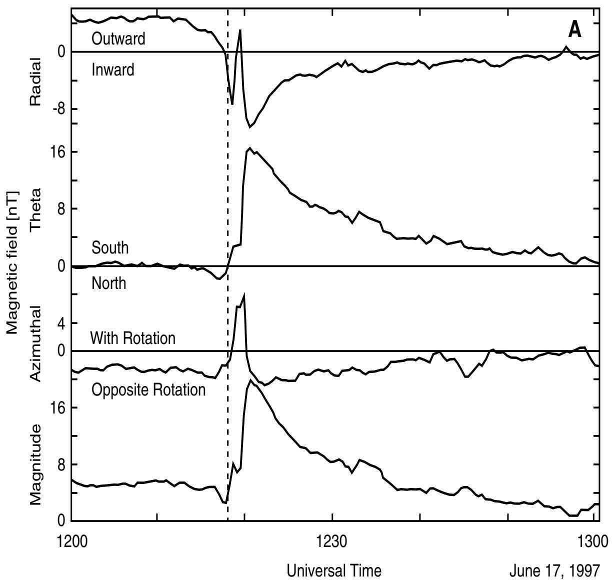


Fig. 19. An example of a reconnection event as observed in the early morning hours at 60 R_J by the Galileo magnetometer (after Russell et al., 1998).

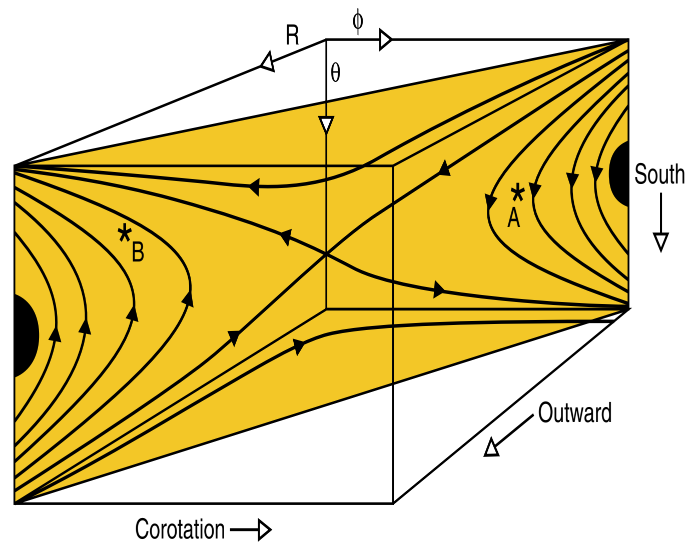


Fig. 20. Interpretation of the magnetic configuration resulting from the reconnection event seen in Figure 19 (after Russell et al., 1998).

There are many ways to estimate this outflow velocity. We can use observations of the Europa plume (Intriligator and Miller, 1982; Russell et al., 1999a); conservation of mass and stress balance in the magnetodisk region (Russell et al., 1999b); and the magnetic field normal to the current sheet (Russell, 2001). These estimates are combined with the above estimate and one made from the Voyager energetic particle data in Figure 18. While there is some variation it is clear that the plasma is being driven outward by centrifugal force at a rate that increases rapidly with increasing distance. We note that at 40 R_J where the typical outflow speed is 40 km/s a flux tube moves 10 R_J in one half a rotation.

These numbers are not unlike those implied by the Vasyliunas model shown in Figure 16. The evidence is clear that mass loading can drive a radial circulation pattern but it is not immediately obvious how a steady state is maintained. The magnetic flux through Jupiter's surface is fixed, determined by the strength of the magnetic dynamo in the interior of Jupiter. However, above the surface of Jupiter this magnetic flux appears to be carried outward by the heavy ions that must be lost from the system to maintain the steady state. Again the answer lies in the reconnection process, much as occurs in the terrestrial magnetotail but with a perhaps unexpected twist.

Figure 19 shows the magnetic field measured by Galileo about 60 R_J behind Jupiter at about 3 LT over a one hour period on June 17, 1997 [Russell et al., 1998]. The magnetic field has rapidly dipolarized and increased in strength a factor of three. Over a 15-minute period it gradually returns to its stretched-out state. The rapid dipolarization clearly was associated with a transient reconnection event of enormous rapidity and strength perhaps propelled by the very low density above and below the night time current sheet that combine with a strong magnetic field to produce a very high Alfven velocity. The strange twist arises when reconnection moves the plasma radially inward and angular momentum conservation can make the plasma speed up in its corotational motion. Figure 20 shows our interpretation of this event [Russell et al., 1998]. Reconnection allows the magnetosphere can rid itself of the added ions while keeping the total magnetic flux constant as it produces islands of magnetized ions that have no net magnetic flux but that can be ejected down the tail. Not coincidentally the amount of magnetic flux involved in reconnection closely matches the magnetic flux involved in the mass loading process (Russell et al., 2001a).

This observation, though, does not completely solve the problem of how the plasma circulates because the now emptied magnetic flux tubes must find their way back to the radius of Io where they can be mass loaded again. In our description above the flow was outward everywhere. The situation can be visualized as a leaking container in which fluid is constantly moving slowly downward in a container. If the container is sealed except for the leak, air must replace the leaking fluid. Air is buoyant and moves rapidly to the top of the sealed container. Thus small, rapidly moving bubbles can maintain steady state even though the fluid moves very slowly downward almost

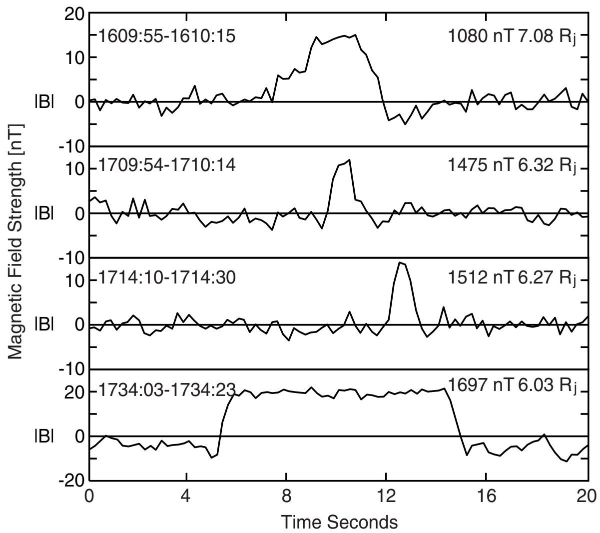


Fig. 21. Examples of depleted flux tubes observed by the Galileo magnetometer in the high resolution data (Russell, 2001b).

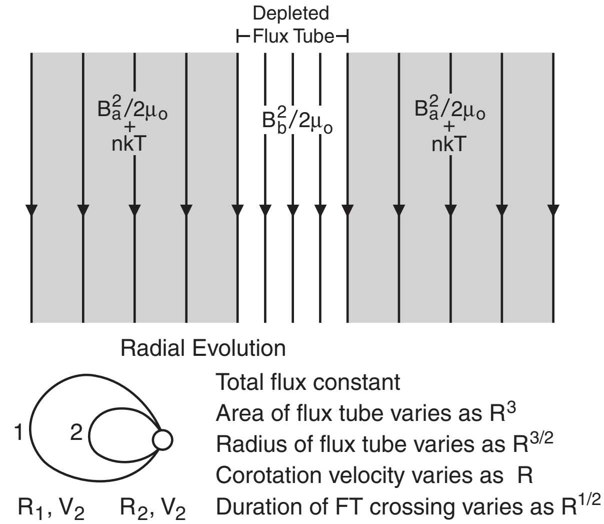


Fig. 22. Schematic illustration of the physics of a depleted flux tube (after Russell et al., 2001b).

everywhere. The equivalent in the jovian magnetosphere would be if thin, empty flux tubes were present. It is indeed possible to detect thin, empty flux tubes in the Io torus where the magnetic field is slightly depressed by the presence of cool plasma of sufficient density to have a diamagnetic effect. Examples are shown in Figure 21. These field changes are small and the effects short-lived in the spacecraft frame so that they are detectable only in high resolution data (Russell et al., 2000b). The physics of these depleted flux tubes is illustrated in Figure 22. Inside the tube there is only magnetic pressure. Outside in pressure balance with this tube is a region of magnetic pressure and plasma pressure. Here the magnetic field must be weaker. The observed differences of about 10 nT are consistent with the low beta values, around 1% expected in the Io torus (Russell et al., 2001b).

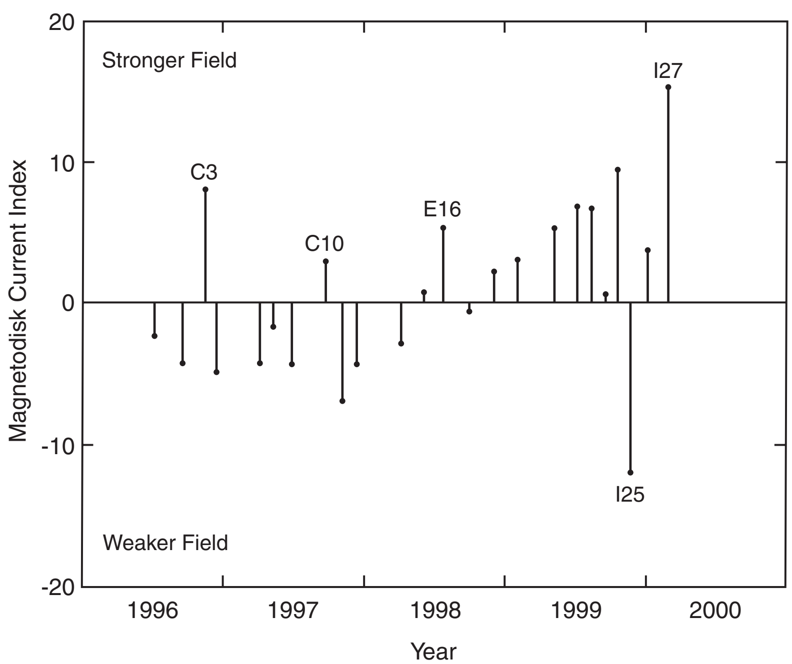


Fig. 23. Magnetodisk Current Index created from the Galileo magnetometer data over the course of the mission (Russell et al., 2001b).

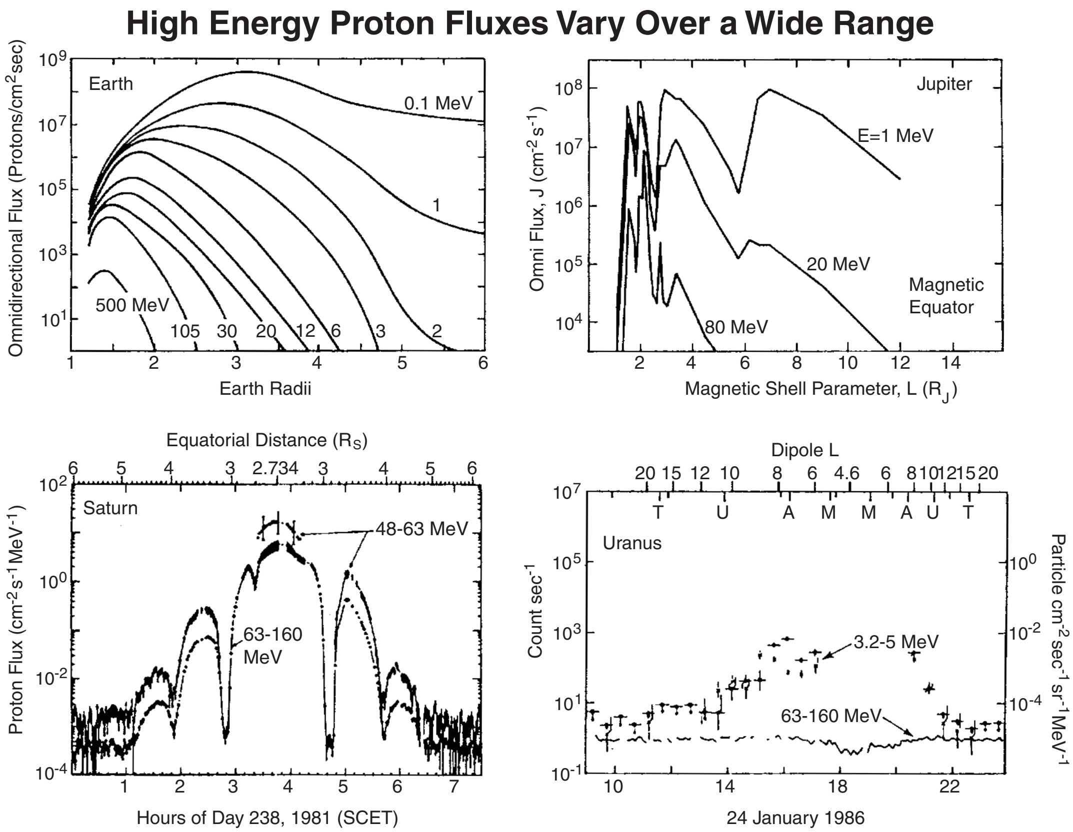


Fig. 24. Energetic proton fluxes at Earth, Jupiter, Saturn and Uranus (D. J. Williams, personal communication, 1995).

We have many reasons to believe this circulation of plasma is unsteady. We noted earlier that the magnetopause standoff distance was bimodal. Reconnection in the nighttime magnetosphere as judged from the size and polarity of the north-south component of the magnetic field is episodic. Various magnetic disturbances in the middle magnetosphere and the inner edge of the magnetodisk region are also episodic. Another way to judge the temporal variability of the system is to create an index that measures the strength of the magnetodisk ring current by calculating the jovian equivalent of a Dst index. This is shown in Figure 23 (Russell et al., 2001c). This index was constructed from measurements near 11-12 R_J but could have been constructed anywhere from about 8 to 15 R_J with little difference. Basically if the mass loading in the torus magnetodisk increases, the field lines stretch over a larger radial range, and the field strength in the inner magnetosphere decreases. As can be seen the magnetosphere is quite variable from month to month at the 10 nT level.

RADIATION BELTS

Earth, Jupiter and Saturn have radiation belts that are intense enough to affect the operation of our spacecraft. There are many processes that can accelerate charged particles to keV energies but the acceleration to energies above a MeV is often puzzling. It is thought that radial diffusion accompanied by conservation of the first adiabatic invariant is important in this process but even if a particle is carried inward from a field of 100 nT to 10,000 nT the energization is only a factor of 100. Moreover, to build up the fluxes of trapped particles to large values the acceleration and transport processes must overcome losses.

Figures 24 and 25 compare the radiation belt fluxes of ions and electrons for Earth, Jupiter, Saturn, and Uranus. Jovian energetic ion fluxes are more intense than those of both Earth and Saturn. Absorption by the rings helps keep Saturn's fluxes more Earth-like. Uranus in contrast has an extremely weak ion radiation belt. The electron fluxes shown in Figure 24 are more similar from planet to planet but again Jupiter has the largest fluxes especially above 10 MeV.

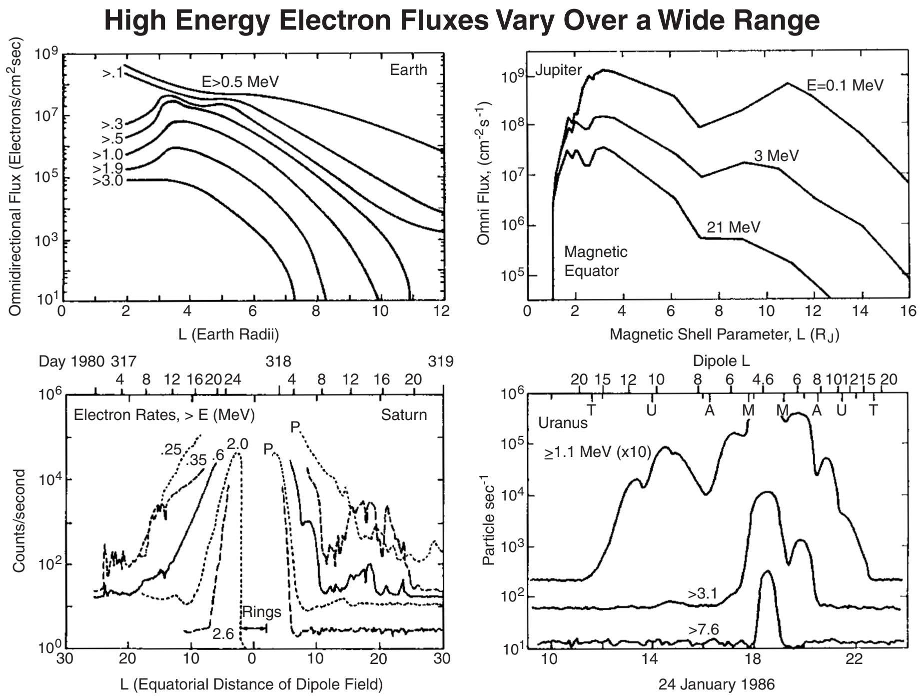


Fig. 25. Energetic electron fluxes at Earth, Jupiter, Saturn and Uranus (D. J. Williams, personal communication, 1995).

On the Earth the creation of "new" energetic radiation belts above 1 MeV is still poorly understood. At Jupiter the fluxes of very energetic particles surprisingly also vary rapidly deep in the magnetosphere. Figure 26 shows background counts of the Galileo star sensor on four passes through the region of the Ion torus. These counts due to highly relativistic electrons varied dramatically from month to month. Russell et al. (2001d) attributed this

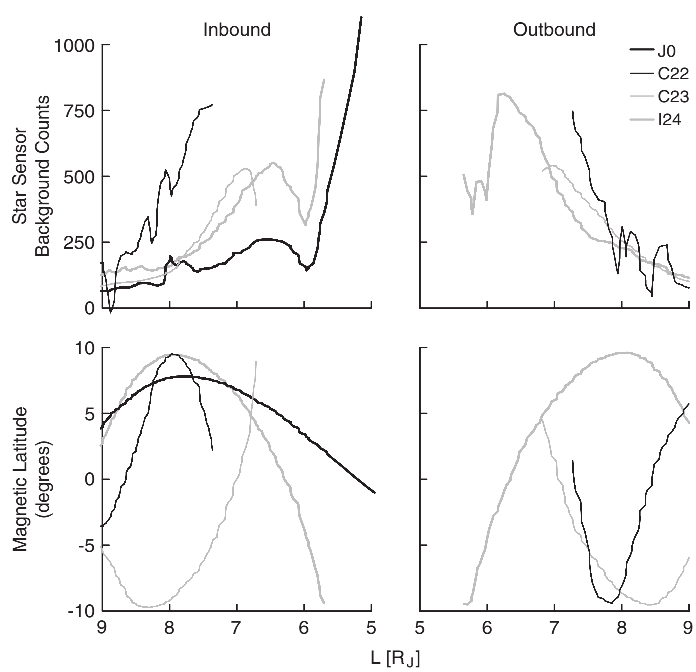


Fig. 26. The variation from month to month of the highly relativistic electron fluxes in the Io torus as inferred from the background counts of the Galileo star sensor (Russell et al., 2001a).

variability to volcanic activity on Io. Even discrete particle injection events in the inner magnetosphere may be caused directly by activity at Io (Russell et al., 2003). Thus the volcanoes on Io may be causing both long-term and short-term changes in the radiation belts, the radio flux and the circulation and dynamics of the jovian magnetosphere. While there may be mass loading effects in other magnetospheres, this intimate temporal coupling may be unique in the solar system.

SUMMARY AND CONCLUSIONS

The dynamic pressure of the solar wind varies dramatically as the density falls with increasing heliocentric distance. This decrease combined with the varying magnetic moments of the outer planets produces a variety of sizes for their magnetospheres. Unlike the terrestrial magnetosphere the size of an outer planet magnetosphere may also be affected by internal sources of plasma that is accelerated to corotational speeds by coupling to the rotating ionosphere by the magnetic field. The change in Mach number with heliocentric distance appears to strengthen phenomena associated with the bow shock but may weaken the solar wind's ability to couple to the dayside magnetopause through reconnection. Reconnection is found at the magnetopause of outer planet magnetospheres but it may be too weak to be a significant driver of plasma circulation in the magnetosphere.

The most significant driver of plasma circulation in the jovian magnetosphere is mass addition at Io that lies beyond synchronous orbit. The mass added stretches the magnetic field outward away from Jupiter. This centrifugal force is eventually sufficient to move the added mass from Io down the tail where reconnection form ion islands that are ejected from the magnetosphere maintaining in the long term both mass and magnetic steady states. The entire process is time varying, causing waves and fluctuations at a variety of time scales. These fluctuations appear to be controlled in some measure by the volcanoes on Io so that the activity of Jupiter's magnetosphere may also vary over a large variety of time scales. This clearly affects Jupiter's radiation belt fluxes, the largest of any outer planet magnetosphere. In the coming years we very much look forward to testing the understanding, developed from the Galileo measurements at Jupiter with the Cassini measurements at Saturn. Perhaps the most important lesson from these data is that kinetic processes, even though they involve very small-scale phenomena, may have global consequences. This is true both for reconnection and for the mass-loading process.

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