

19 Planetary Magnetospheres

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The study of planetary magnetospheres began almost a half century ago with the launch of Sputnik and Explorer 1, the first artificial satellites of the Earth. The exploration of other magnetospheres started not long after. Our understanding of our own space environment has grown ever deeper with the passing years as flotillas of spacecraft have gradually acquired measurements whose interpretation provides a good (although as yet imperfect) understanding of Earth's environment in space. Our exploration of the magnetospheres of other planets has also progressed brilliantly but the high cost of planetary probes inevitably implies that we understand less about remote magnetospheres than about our own. Fortunately even limited data are of immense value in advancing the study of comparative magnetospheres because they reveal how magnetospheric processes respond to changes of scale, of rotation rate and of solar wind structure in the vicinity of the planet. This article addresses the topic of planetary magnetospheres by contrasting their properties with those familiar at Earth. The differences are related to key dimensionless parameters of the plasma flowing onto the different bodies of the solar system and to key properties of the central bodies such as the strength and symmetry of the magnetic field at the planet's surface, the size and rotation period of the planet, the nature of its plasma sources and the conductivity of its surface layers.

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19.1 Introduction

Laboratory scientists have the luxury of being able to probe their samples repeatedly under controlled conditions over a range of underlying parameters such as density and pressure. Magnetospheric scientists have little control over the conditions of their investigations. To be sure, the responses of the terrestrial magnetosphere to changes in solar wind dynamic pressure and magnetic field orientation have been extensively analyzed, but the variations are uncontrolled, narrowly bounded and some important internal parameters of the system do not change. Fortunately some other planetary magnetospheres exist and some of their properties differ significantly from those applicable to the terrestrial magnetosphere. This chapter emphasizes the physical parameters that control the outcome of the interaction of a flowing plasma with a magnetized body and describes some of the interesting ways in which the magnetospheres of other magnetized bodies in the solar system differ from the one with which we are familiar. Armed with such information, we can speculate on how Earth's magnetosphere itself may have changed over geological time.

19.2 Parameters that Control Magnetospheric Configuration and Dynamics

A magnetosphere forms when a plasma flows onto a magnetized body such as a planet or a moon. Critical to the form of the interaction are the properties of the plasma, some of which are effectively expressed in terms of dimensionless ratios including the ratio of the Alfvén speed and the sound speed to the speed of the plasma measured in the rest frame of the planet and the ratio of the plasma pressure to the magnetic pressure. At Earth the changing orientation of the interplanetary magnetic field contributes significantly to temporal variations, implying that orientation is a control parameter but the importance of this element of solar wind control varies from one planet to another. Other parameters that govern the interaction are intrinsic to the planet: its radius and rotation rate, the strength and symmetry of the magnetic field at its surface, the conductivity of its surface and upper atmosphere, its neutral exosphere and the location and composition of any moons and rings. Finally, the scale of the interaction region is determined by the dimensionless parameter that relates the

energy density of the incident solar wind to the energy density in the magnetic field and the magnetospheric plasma near the boundary.

One must consider how to restrict the subject of this chapter, recognizing that comets and planets or moons lacking permanent internal magnetic fields also perturb the solar wind, creating regions of disturbed flow that have much in common with the magnetospheres of magnetized planets. The reader is referred to Chap. 20 (The Solar-Comet Wind Interaction) for a discussion of the cometary interaction. That discussion reveals that an unmagnetized body, like a magnetosphere, greatly modifies plasma properties in the space surrounding it and that the external field drapes around the body extending the interaction region downstream in the antisolar direction. Analogous interaction regions form around the unmagnetized moons of Jupiter (Io, Europa, and Callisto), the largest moon of Saturn (Titan). None of these cases will be discussed in this chapter, which instead focuses on the true magnetospheres of the solar system: Mercury, Earth, Jupiter, Saturn, Neptune, Uranus and Jupiter's moon Ganymede. To this list some would like to add Mars, which lacks a planet-wide field but does have regions where the magnetic field is sufficiently intense to prevent the solar wind from flowing onto some parts of its surface. The localized fields create structures that resemble solar arcades. Table 19.1 gives some of the key parameters for the magnetospheres that are discussed in this chapter. Extensive tables of properties of the bodies discussed in this chapter can be found in Kivelson and Bagenal (2005).

19.2.1 Properties of the Flowing Plasma

A magnetosphere responds to various forms of pressure in the plasma that confines it. In a magnetized plasma, the total pressure P , exerted in the direction of the flow, is given by

$$P = \rho u^2 + p + B^2/2\mu_0 \quad (19.1)$$

where the terms represent the dynamic pressure, the thermal pressure and the magnetic pressure expressed in terms of the density, ρ , flow velocity, \mathbf{u} , thermal pressure, p , and magnetic field, \mathbf{B} . The thermal pressure has been assumed isotropic. In steady state, at the boundary of the magnetosphere the external pressure balances the internal pressure. The form of the magnetosphere is

Table 19.1. Properties of planet and of plasma flowing onto its magnetosphere

	Radius (km)	Surface equatorial field (nT)	Dipole tilt and sense	Sidereal rotation period	Density of of external plasma**	Dynamic pressure of external plasma (nPa)*	Magnetic field of external plasma (nT)**
Mercury	2440	140 to 400	$\sim 10^\circ$ *	59 days	$\sim 50/\text{cm}^{-3}$	15	20
Earth	6373	31,000	$+ 10.8^\circ$	23.9 h	$8/\text{cm}^{-3}$	2	8
Mars	3390	<10	–	24.6 h	$3.5/\text{cm}^{-3}$	1	3.5
Jupiter	71,398	428,000	$- 9.6^\circ$	9.8 h	$0.3/\text{cm}^{-3}$	0.1	1
Saturn	60,330	22,000	0.0°	10.7 h	$0.1/\text{cm}^{-3}$	0.03	0.5
Uranus	25,559	23,000	-59°	15.5 h	$0.02/\text{cm}^{-3}$	0.005	0.3
Neptune	24,764	14,000	-47°	15.8 h	$0.008/\text{cm}^{-3}$	0.002	0.2
Ganymede	2634	720	4°	7.2 days	$100 \text{ AMU}/\text{cm}^3$	1	100

* The dipole tilt of Mercury is not well determined. This value from Slavin (2004)

** The properties of the solar wind vary greatly; hence the values are approximate

Table 19.2. Parameters relevant to the structure and dynamics of planetary magnetospheres*

	(a) $(B_{\text{surf}}^2/2\mu_o)/\rho_{\text{ext}}u_{\text{ext}}^2$	Upstream magnetosonic Mach number**	Distance to magnetopause (planetary radii or noted)	$0.1 v_{\text{sw}}/v_{\text{rot}}$ near nose of magnetopause
	(b) $(B_{\text{surf}}^2/B_{\text{ext}}^2)$			
Mercury	(a) ~ 1	6	1.5	3×10^4
Earth	(a) 4×10^5	7	10	9
Mars	(a) < 0.04	8	–	–
Jupiter	(a) 7×10^8	10	70	0.04
Saturn	(a) 7×10^7	12	20	0.2
Uranus	(a) 4×10^7	13	18	0.7
Neptune	(a) 4×10^7	15	24	0.6
Ganymede	(b) 50	0.4	1.6	∞

* The properties of the solar wind vary greatly; hence the values are approximate average values

** The values of the magnetosonic Mach numbers are from a model tabulated by Slavin et al. (1985), rounded to integer values

dictated by the dominant term in the external pressure. When dynamic pressure dominates as in the solar wind, the magnetosphere is bullet-shaped and extended along the direction of external plasma flow as in Fig. 19.1, left, which represents the magnetosphere of Mercury and compares it with Earth's magnetosphere. When the magnetic pressure dominates the ambient plasma, as in the vicinity of Jupiter's magnetized moon Ganymede, the magnetosphere formed by interaction with the incident flowing plasma is rod- or cylinder-shaped and roughly aligned with the external magnetic field as illustrated in Fig. 19.1, right. The form of the magnetosphere is thus seen to depend on the ratios of the differing forms of pressure in the surrounding plasma. Even when the

dynamic pressure dominates, as in the solar wind, its contribution to magnetospheric confinement is a function of the angle between the flow and the local surface normal. Dynamic pressure controls the sunward-facing boundaries of planetary magnetospheres, including Earth's, whereas thermal and magnetic pressure confine the magnetosphere on the distant flanks where the flow direction is roughly antiparallel to the normal.

Dimensionless parameters that express the relative importance of the three terms in (19.1) are the Alfvén Mach number u/v_A where $v_A = B/(\mu_o\rho)^{1/2}$ is the Alfvén speed whose square is the ratio of the energy density in the flow to the magnetic energy density, the sonic Mach number whose square is the ratio of the dynamic

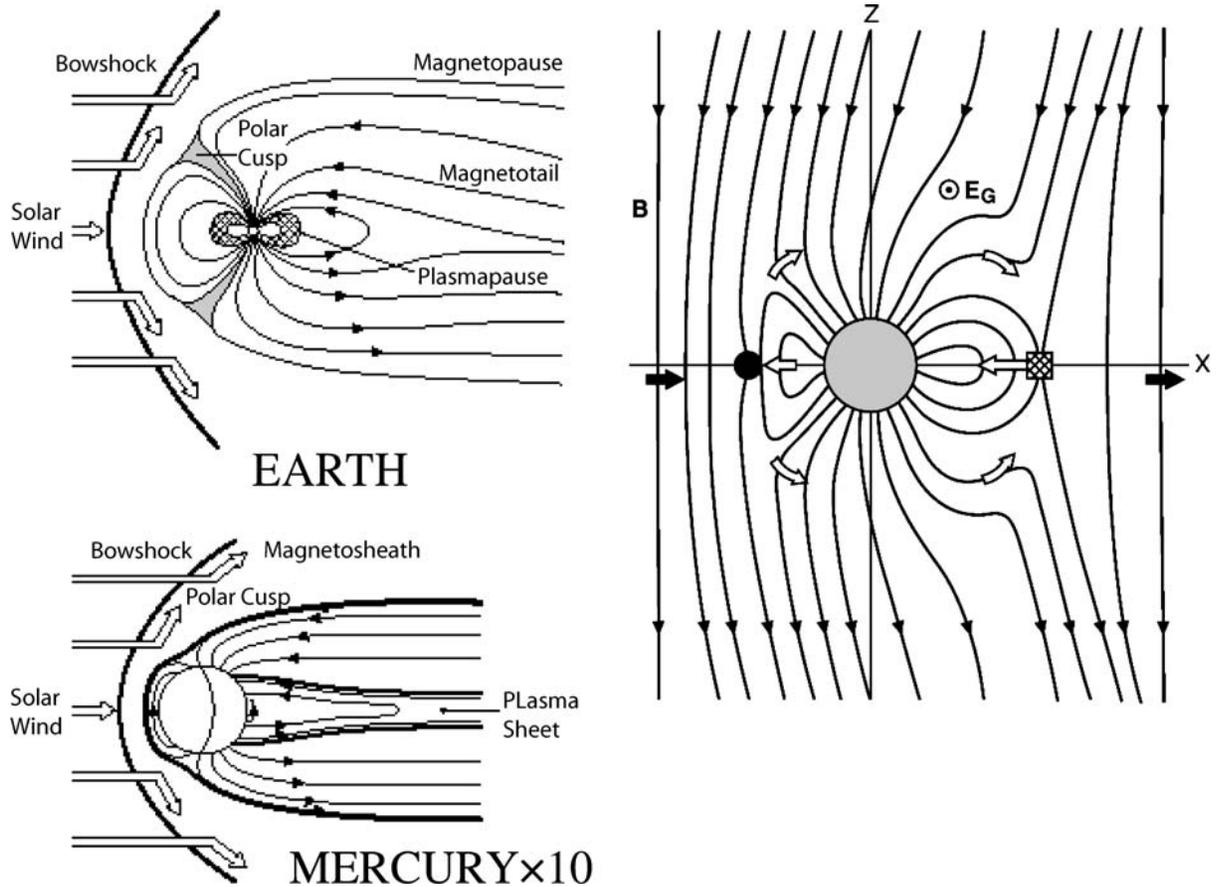


Fig. 19.1. *Left:* Schematic of Mercury's magnetosphere (*below*) compared with Earth's magnetosphere (*above*) (Kivelson and Bagenal, 1998). *Right:* Schematic of a cut through the plane of the flow and the upstream field through the center of Ganymede's magnetosphere. In all schematics, the plasma flow is from the *left* and is represented by *broad arrows*

to the thermal pressure (to within a factor of order 1) and the plasma $\beta [= p/(B^2/2\mu_0)]$ which is the ratio of the thermal to the magnetic pressure. For normal and even for most extreme conditions in the solar wind, the dynamic pressure dominates, so both Mach numbers are >1 ; a shock forms upstream of all the planets and the magnetospheres are bullet-shaped. Ganymede, embedded in the flowing plasma of Jupiter's magnetosphere, is the exception. In its environment (see Table 19.2), the Alfvén Mach number is normally <1 ; no upstream shock forms and the magnetic pressure dictates the structure of the magnetosphere.

External and internal plasmas interact not only through hydromagnetic forces but also through reconnection of magnetic fields, a process efficient in accelerating particles and increasing the stress on the

system. Therefore, it is not only the magnitude of the magnetic field but also its direction that is relevant to the dynamics of a magnetosphere. At Earth, reconnection with the solar wind is fundamental to geomagnetic disturbances. It has been securely established that the rate of energy input into the magnetosphere is controlled by $\mathbf{u}_{sw} \times \mathbf{B}_{sw}$ (where \mathbf{u}_{sw} and \mathbf{B}_{sw} are the flow velocity and the magnetic field of the solar wind and the negative of the cross product is the electric field). Maximum power for a fixed solar wind speed, density and field magnitude arises where \mathbf{B}_{sw} is antiparallel to Earth's equatorial field, a configuration that favors reconnection on the low latitude dayside magnetopause. The significance of the field orientation in the upstream plasma is discussed for other bodies in later sections.

19.2.2 Properties of the Planet or Moon

It is not only the external plasma conditions that control the configuration of a magnetosphere and its dynamics. Various properties of the central planet or moon such as the planet's rotation rate, the strength of its magnetic field as characterized by its surface magnitude and the orientation of the dipole moment relative to the spin axis are also critical. The planetary radius that establishes the spatial scale of the interaction region varies by one and a half orders of magnitude between Mercury and Jupiter. The ratio of the time for the solar wind to flow from the nose of the magnetosphere to the terminator plane to the period of planetary rotation gives a measure of the relative importance of rotation. For Jupiter this ratio is roughly a third of the planetary rotation period and rotation dominates much of magnetospheric dynamics. At Earth, where the ratio is 1/540, rotation is far less important. For Ganymede and Mercury, the effects of planetary rotation are negligible as will be discussed below. Magnetospheric dynamics differ greatly in the two limits.

Widely separated regions within a magnetosphere are strongly coupled by field-aligned currents and this implies that the electrical conductivity of the central body is a key parameter in constraining the dynamics of the system. Currents may close in an ionosphere or through the surface/interior of the body.

Finally it is interesting to recognize that some magnetospheres are significantly affected by plasma introduced within their boundaries either from an ionospheric source or when neutrals that escape from the exosphere or from rings and moons gravitationally bound to the planet are later ionized. Ionization transfers mass to the plasma. Charge exchange extracts momentum from it. The giant planet magnetospheres, especially those of Jupiter and Saturn, owe many of their unique properties to the presence of such plasma sources.

19.2.3 Dimensionless Ratios Controlling Size and Dynamics

In steady state, the total pressure given in (19.1) must be the same on the two sides of the magnetopause, the boundary of the magnetosphere. For planets other than Jupiter and Saturn, the internal pressure near the boundary is dominated by the magnetic pressure. The scale of the magnetosphere is thus controlled by

$$(B_{\text{surf}}^2/2\mu_o)/P_{\text{ext}} \quad (19.2)$$

where P_{ext} is the total pressure of the external plasma. For planetary magnetospheres, the relevant ratio is that of the magnetic pressure of the internal magnetic field at the surface of the body, to the dynamic pressure of the external plasma expressed in terms of the solar wind density, ρ_{sw} , and the flow speed. Thus the critical ratio, S_M , is

$$S_M = (B_{\text{surf}}^2/2\mu_o)/\rho_{\text{sw}}u_{\text{sw}}^2 \quad (19.3)$$

where B_{surf} is the dipole field magnitude at the surface of the planet. When S_M is of order 1, the magnetosphere cannot extend far above the surface in the sunward direction. When $S_M \gg 1$, the standoff distance can be tens of planetary radii. It follows from Table 19.2 that the magnetosphere of Mercury cannot extend far above the surface, that the global field of Mars cannot stand off the solar wind, and that all of the other magnetized planets have magnetospheres that extend to large distances above the surface of the body. Ganymede's nose distance is determined by the ratio of magnetic pressures and is found to lie about $1 R_G$ (Ganymede radius = 2634 km) above the surface.

As described in Sect. 19.2.1, the dynamics of the terrestrial magnetosphere are controlled to a considerable extent by reconnection with the magnetic field of the solar wind. Conditions for reconnection with the solar wind are at least intermittently satisfied at all the magnetized planets. However, the relative importance of reconnection and internally driven rotation in driving the dynamics of the system varies from planet to planet. Rotation is particularly important at Jupiter where the large spatial scale and the short rotation period imply that, in the outer magnetosphere, centrifugal stresses dominate those imposed by reconnection. A comparison of the speed of plasma corotating with the planet just inside the magnetopause (u_{corot}) with the maximum convective speed that is imposed on the plasma of the outer magnetosphere by the cross magnetosphere electric field arising from dayside reconnection (u_{reconn}) confirms this statement. (The convective speed refers to flow perpendicular to the magnetic field.) Assuming a reconnection efficiency, α , u_{reconn} can be estimated from the electric field of the solar wind, $|E_{\text{sw}}| = u_{\text{sw}}B_{\text{sw}}$ as $u_{\text{reconn}} = \alpha u_{\text{sw}}B_{\text{sw}}/B_{\text{msf}}$ with B_{msf} the magnetic field of the outer magnetosphere. The field strength typically

increases by roughly a factor of 5 between the solar wind and the dayside outer magnetosphere. Accordingly, reconnection-imposed flow just inside the dayside magnetopause is $0.2\alpha u_{sw}$ and for a characteristic solar wind speed of 400 km/s a flow speed of $\sim 80\alpha$ km/s can be attributed to reconnection. Estimates of α are of order 0.1 (Kennel and Coroniti, 1977) or as high as 0.18 (Slavin and Holzer, 1978). For comparison with the effects of rotation, one must correct for the fact that the plasma of the outer magnetosphere does not corotate with the planet. Corotation requires coupling to the ionosphere through field-aligned currents linking to the ionosphere. At large distances, observations show that corotation is not fully imposed. An efficiency factor β can be introduced to account for the fraction of the corotation speed that is actually observed near the magnetopause. At Jupiter, β is ~ 0.3 to 0.5. Then the rotation speed is $\beta r_M \Omega_p$ where r_M is the magnetopause nose distance and Ω_p is the angular frequency of planetary rotation. Using $\alpha = 0.2$ as an approximate upper limit, the dimensionless parameter $\sim 0.1u_{sw}/r_M\Omega_p$ must be larger than 1 for reconnection to dominate internal rotation. The ratio is >1 for Earth and Mercury whose magnetospheres are dominated by reconnection, $\ll 1$ for Jupiter, which is dominated by rotation, and somewhat smaller than 1 for Saturn, implying that both rotation and reconnection are important.

19.3 A Tour of Planetary Magnetospheres

It is convenient to tour the planetary magnetospheres in groups. The first group, the mini-magnetospheres, includes Mercury and Ganymede. In both cases rotational effects are either negligible or absent and the properties of their inner boundaries differ greatly from those familiar at Earth. They differ in some ways from one another because they form in very different plasma environments. The giant magnetospheres of the rapid rotators, Jupiter and Saturn, form a second group distinguished by important effects of planetary rotation and the significant contribution of internal plasma sources such as moons and rings. The third group, Uranus, Neptune and the heliosphere, contains magnetospheres that do not readily fall into either of the first two categories. A few remarks on Mars conclude the tour of planetary magnetospheres. Selected properties of the central bodies and of the plasma within which they are embedded

are given in Table 19.1. Dimensionless parameters relevant to the discussion are given in Table 19.2.

19.3.1 Mini-Magnetospheres

In this chapter, the designation mini-magnetosphere applies to magnetospheres for which the shortest distance to the magnetopause is less than or of the order of one planetary radius above the surface, a requirement that singles out the magnetospheres of Mercury and Ganymede. An excellent review of Mercury's magnetosphere is provided by Slavin (2004). For background on Ganymede's magnetosphere, see Kivelson et al. (2004). These magnetospheres are so small that radiation belts, familiar from studies of Earth, cannot form. They rotate so slowly that the concept of a plasmasphere must be abandoned. In both systems, volatiles from which are formed pickup ions may be important to consider. Length and time scales differ greatly from those familiar from the study of Earth. One can argue that the distant neutral line in Mercury's magnetotail will form beyond 30 planetary radii downtail, a distance covered by the solar wind in ~ 3 min. Contrast this with Earth where it takes the solar wind about 1 hour to flow to the downtail distant neutral line. Data support the view that time scales are governed by these characteristic values.

Simple parallels to Earth do not apply at Ganymede where a low beta plasma flowing at sub-Alfvénic speed confines the magnetosphere. Unique to this magnetosphere are the absence of an upstream shock, the unusual configuration that links it to Jupiter's ionospheres and the quasi-steady form of the external magnetic field that leads to a steady form of reconnection. Much of what we know about Ganymede comes from Galileo's flybys, but simulations now underway are revealing interesting aspects of the unmeasured portions of the system.

Structure and Dynamics

The magnetospheres of Mercury and Ganymede share many characteristics with Earth's magnetosphere. As can be seen in the schematic of Fig. 19.1, a distinct boundary, the magnetopause, separates the internal and external plasmas and in both cases, the polar cusp permits direct penetration of external plasma. The internal fields are dominated by dipolar fields with northward

equatorial field orientation. In the presence of an external magnetic field oriented southward, reconnection appears to link internal and external fields.

At Earth stochastic variations of the magnitude and orientation of the external magnetic field control much of the internal dynamics of the system such as storms and substorms. When the interplanetary magnetic field remains southward oriented, magnetic flux is added to the magnetosphere. Substorms return the newly added magnetic flux to the solar wind.

Little is known about Mercury's magnetosphere because measurements are available only from two brief flybys by the Mariner 10 spacecraft that were within the magnetosphere for only about 30 min. Figure 19.1 shows the dayside magnetopause standing above the surface but it is likely that at times of extremely high solar wind dynamic pressure, the dayside magnetopause moves down to the surface.

During the pass through Mercury's magnetosphere shown at the top of Fig. 19.2, the interplanetary magnetic field seems to have remained northward oriented. The smooth variation of the magnetic field magnitude reflects changes linked to the change of distance from the planet. During the pass shown at the bottom of the figure, the interplanetary field was initially northward-oriented but it rotated southward during the pass. On this pass, several substorms were observed. One can estimate the rate of transport of magnetic flux in the magnetotail toward the neutral sheet, assuming that 10% of the solar wind electric field is imposed within the magnetosphere and that the lobe field is comparable with the solar wind field at large downstream distances. For Earth these assumptions imply that it requires ~ 50 min for a flux tube to flow across a lobe of width $\sim 20 R_E$ and that during this time the solar wind flows $\sim 200 R_E$ downstream, reaching the typical distance of the distant neutral line in the tail. For southward oriented IMF, terrestrial substorms recur on average every ~ 3 h or roughly 3 times the estimated transport time. For Mercury, the same analysis implies a transport rate of 1 min per R_M (R_M is a Mercury radius = 2439 km) across the tail. In the 3 min required for a flux tube in the magnetotail to move north-south across a lobe of width $\sim 3 R_M$ (see Fig. 19.1), the solar wind would flow $\sim 30 R_M$ downstream, a plausible location for a neutral line. If substorms at Mercury recur at intervals of a few minutes or roughly the estimated transport time, then the oc-

currence of multiple substorms during a brief Mercury encounter is plausible. It is uncertain whether the substorm at Mercury includes a phase during which flux is stored in the magnetotail as in the growth phase of terrestrial substorms or if the magnetosphere responds to changes in the solar wind without delay.

Although one must await data from the upcoming MESSENGER (arrival at Mercury on March 18, 2011) and Bepi-Columbo (to be launched in 2012) missions to document the properties of its magnetosphere, it is amusing to anticipate that because of Mercury's considerable orbital eccentricity, some features of the magnetosphere are likely to vary at the 88 day orbital period. With aphelion at 0.47 AU and perihelion at 0.36 AU, the average solar wind Mach number should vary by a factor of 1.3 and the field magnitude and plasma density by a factor of 1.7 every Mercury year. Consequently it is likely that average properties of the bow shock (shock strength, standoff distance) and of "hermeamagnetic" activity may be slowly modulated.

The plasma and field properties of the Jovian plasma flowing onto Ganymede, also vary periodically with a 172 h period because of Jupiter's dipole tilt. (Short period fluctuations are also present but only at amplitudes of order 10% of the background levels.) The external field changes little in magnitude but slowly rocks radially through an angle of $\pm 50^\circ$ always having a southward orientation.

Despite the field configuration consistently favorable to reconnection, there have been no reports of activity at Ganymede analogous to terrestrial substorms. One must consider whether the dwell in the magnetosphere has been sufficiently long for Galileo to have observed substorm activity during the 6 flybys. Again we must estimate the expected interval between substorms. At the ~ 150 km/s flow speed of the Jovian plasma, it takes ~ 3 min for the external flow to carry plasma across the $\sim 10 R_G$ (R_G , Ganymede radius = 2634 km) width of the magnetosphere to the downstream neutral line (see Fig. 19.1). Analogy with Earth suggests that some small multiple of this number provides a reasonable estimate of substorm recurrence time. If substorms are similar to those observed at Earth, one would expect them to occur every 10 or so minutes. Galileo's multiple passes through Ganymede's magnetosphere provided more than 2.5 h of data within the magnetopause. The fact that substorms were not identified during the Galileo

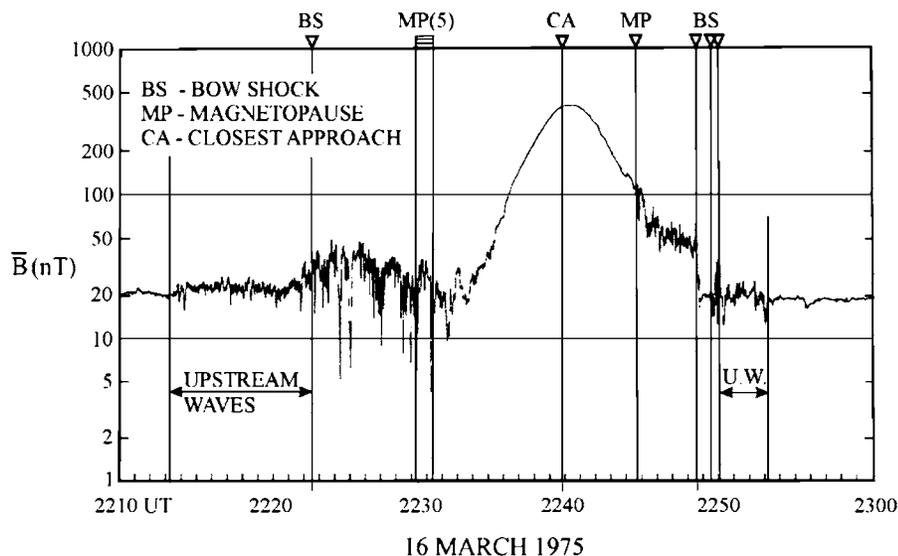
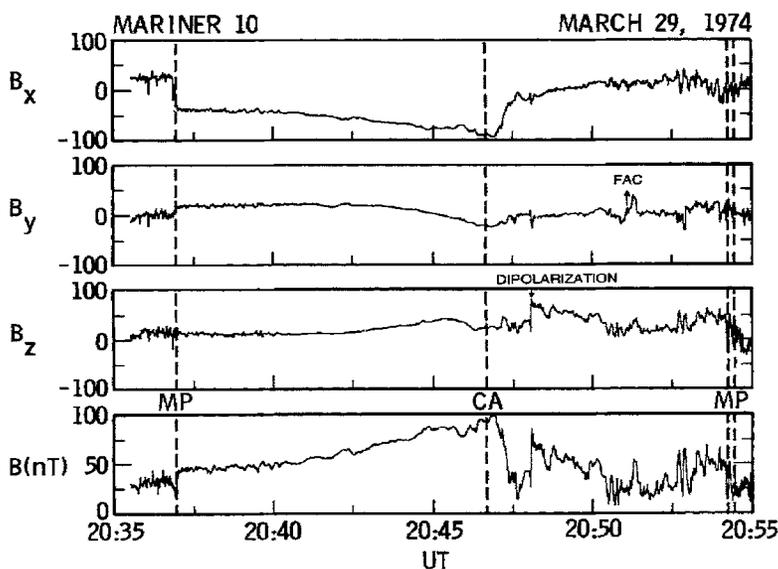


Fig. 19.2. Above: The magnitude of the magnetic field observed by Mariner 10 during the third fly-by of Mercury on March 16, 1975 (Grard and Balogh, 2001). Below: Mariner 10 magnetic field observations made during the first flyby on March 29, 1974 (Slavin, 2004)



flybys suggests either that substorms do not occur or that they have characteristics quite different from those observed at Earth. The cycling of magnetic flux from the external Jovian plasma through Ganymede's magnetosphere appears not to function through unsteady internal reconnection. Reconnection and subsequent transport may be a relatively steady state process, similar to what at Earth would be termed steady magnetospheric convection. If this is the case, the data

from Ganymede gives insight into a particular type of process that occurs at Earth. However, more complete documentation is needed to support this interpretation.

In the magnetospheres of Mercury and Ganymede, rotation is absent or irrelevant. Ganymede rotates about its axis once every 7.15 Earth days, but this is also the period of its orbital motion, so the direction of the external plasma flow changes in phase with the rotation. Thus, relative to the principal axis of the magneto-

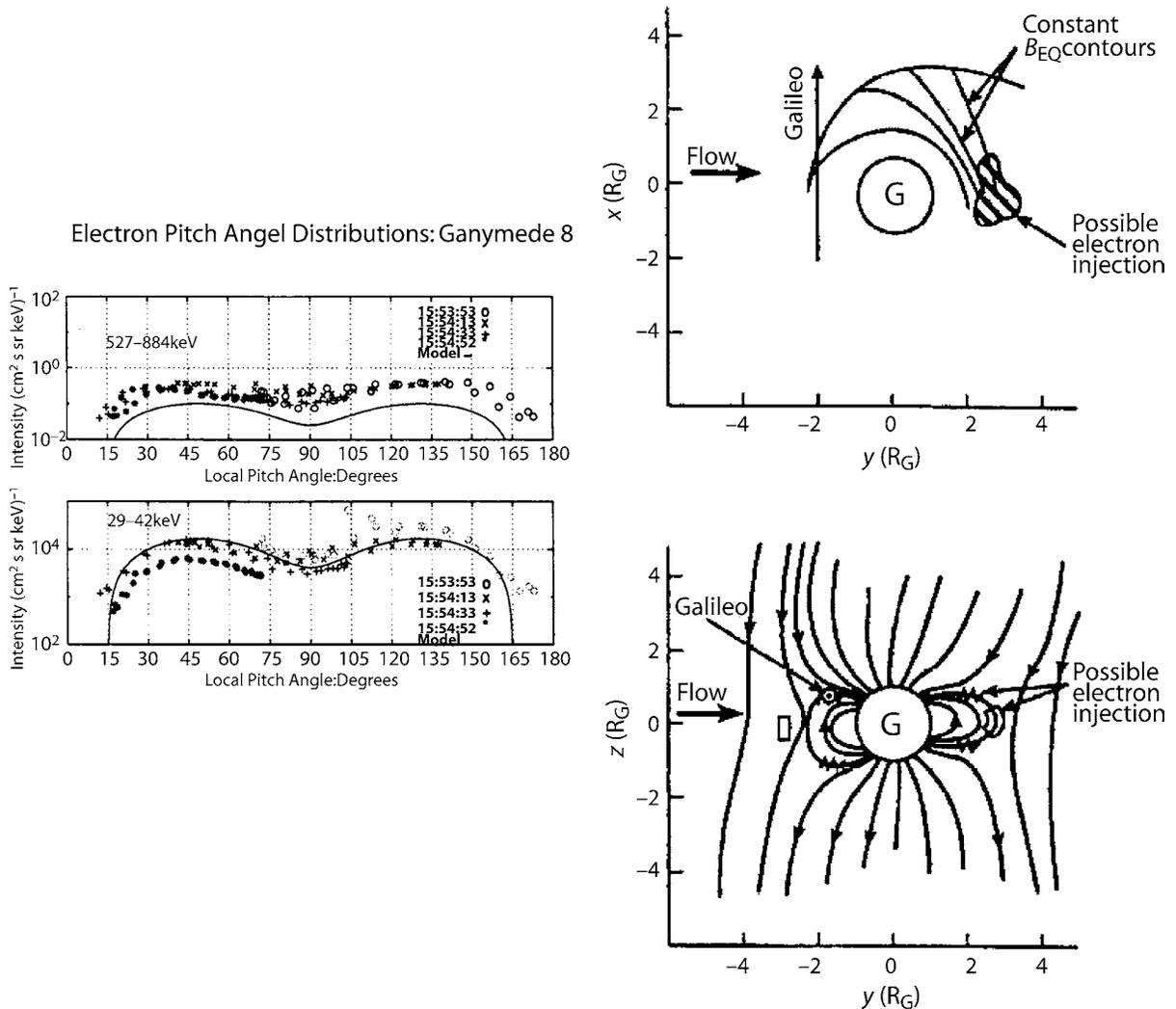


Fig. 19.3. Energetic electrons in the upstream magnetosphere of Ganymede (Eviatar et al., 2000). *Left:* Pitch angle distributions at two different energies, both showing the butterfly distribution produced by drift shell splitting. *Right:* Schematics in the equatorial plane showing nominal electron drift paths (*above*) and a cut through the field and the flow showing proposed particle injection regions and regions in which electrons are detected (*below*)

sphere, aligned with the direction of upstream flow, Ganymede does not rotate at all. Mercury's rotation period is 59 Earth days, but relative to the planet-Sun line, the principal axis of the magnetosphere, the rotation period (P_M) is 176 days. At Earth, rotation is dominant inside the plasmopause, a boundary between relatively high density plasma ($\gtrsim 100$ ions/ cm^3) with a predominantly ionospheric source and low density

magnetospheric plasma. The characteristic distance of the plasmopause from the center of rotation is determined by the location where the corotation speed equals the speed of convection imposed by the solar wind. This distance, L_{pp} , expressed in units of planetary radii is given by

$$L_{pp} = (20\pi B_{\text{surf}} R_p / v_{sw} B_{sw} P_M)^{1/2} \quad (19.4)$$

Here R_p is the planetary radius and it is assumed that reconnection with the solar wind occurs at 10% efficiency. For Earth, the critical distance is $L_{pp} \sim 6$ whereas at Mercury $L_{pp} \sim 0.02$ and at Ganymede $L_{pp} = 0$, i.e., there can be no plasmasphere for either system because the nominal plasmapause location lies deep within the planet.

Energetic Particles in Mini-Magnetospheres

Despite the small scales of the two magnetospheres that we are considering, both have significant populations of energetic particles (tens to hundreds of keV per ion). The mechanisms through which particles are accelerated to such high energies are not yet fully established, but the loss processes are quite well identified and only the existence of efficient acceleration can account for the fluxes that are observed.

Two sources of energetic particles, the magnetopause and the neutral sheet in the magnetotail, are probable, both providing acceleration through reconnection. At Mercury, the increase of energetic electron fluxes by more than four orders of magnitude occurs at the times identified as substorms by the rotation of the magnetic field. At Ganymede, energetic electrons are found on dipolar field lines even without evidence of substorm-like behavior (Fig. 19.3).

For both magnetospheres, the drift paths of energetic particles are controlled by the convection electric field and gradient-curvature drift. Any low energy particles whose source is in the center of the magnetotail have a high probability of being absorbed by the central body (planet or moon) and little chance of drifting around it to the upstream side. Characteristic drift paths for energetic electrons are indicated for Ganymede in Fig. 19.3. In a small magnetosphere, losses also occur through pitch angle scattering into the large loss cones. Even on the outermost closed drift paths, the loss cone becomes bigger than 30° at some portion of a nominal circular drift path as illustrated for Mercury in Fig. 19.4. Assuming strong diffusion, 13% of the particles on this drift path are lost each drift period and the fractional loss per drift period increases rapidly as the radial distance decreases. For equatorial particles of charge q and perpendicular energy W_\perp at distance LR_M from the dipole center, the drift period is $qB_o 2\pi R_M^2 / 3W_\perp L$ or $85/W_\perp$ (keV) L (in minutes) for Mercury. A 50 keV particle at $L = 1.5$ has a drift period of ~ 1.1 min, implying that energetic particles injected into the magnetosphere are likely to remain

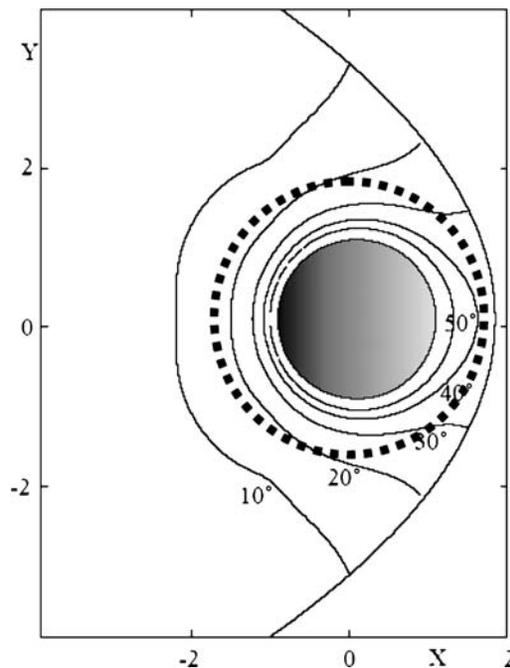


Fig. 19.4. Contours of constant loss cone in Mercury's magnetosphere and a nominal circular drift orbit of a particle in the outer magnetosphere. Modified from Grard and Laakso (2005)

for only a few minutes. Drift periods at Ganymede are roughly twice as long as a given L .

There are no measurements from the day side of Mercury's magnetosphere, but passes on closed field lines upstream of Ganymede show that the flux of energetic electrons increases with distance from Ganymede and falls off in an energy dependent manner as seen in Fig. 19.5. Electrons accelerated by reconnection downstream of Ganymede drift around on the Jupiter-ward side only if their energy is sufficiently high for gradient-curvature drift to dominate. However, they are on open drift trajectories as illustrated in Fig. 19.3, so some radial diffusion is needed to bring them onto closed drift trajectories. The fact that significant fluxes of electrons are found on the dayside magnetosphere despite strong loss mechanisms and that the fluxes are rather symmetric about the central magnetospheric plane containing the magnetic field and the flow suggests that either radial diffusion is strong or that several different injection mechanisms must be acting. The processes that account for the energetic electron populations of the mini-magnetospheres are not yet well understood.

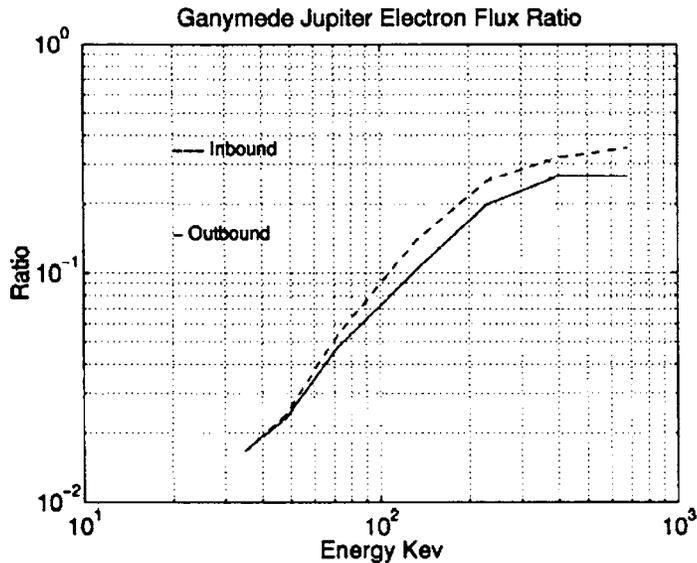


Fig. 19.5. Ratio of electron intensities observed on Ganymede 8 at closest approach on closed magnetic field lines on the upstream side of the magnetosphere to the intensity of ambient Jovian magnetospheric electrons beyond Ganymede's magnetopause as a function of energy. (Eviatar et al., 2000)

Waves in Mini-Magnetospheres

Standing waves have been identified on closed flux tubes. The wave periods are of the order of an ion gyroperiod, so the waves differ from field line resonances typical at Earth. The waves observed at Mercury were quite monochromatic whereas at Ganymede, the waves displayed harmonic structure. The largest amplitude waves in these magnetospheres, also in the ion gyroperiod range, are on the magnetopause boundary and are most probably Kelvin–Helmholtz waves. An example from a pass through Ganymede's magnetosphere is shown in Fig. 19.6. In an analysis of surface waves at Mercury, K.-H. Glassmeier et al. (2003) have pointed out that the applicable gyrotronic theory requires the introduction of a non-diagonal dielectric tensor. The same situation must apply at Ganymede where it should be possible to investigate how the properties of surface waves change as the angle between the internal and external fields change. There is still much to be learned about waves in Ganymede's magnetosphere in anticipation of future analyses of the wave properties of Mercury's magnetosphere.

The Closure of Magnetospheric Currents

Despite the small scale of the mini-magnetospheres, the gyroperiods and gyroradii of the thermal plasma

ions are sufficiently small that a magnetohydrodynamic (MHD) description is appropriate for interpreting most of their properties. In this limit, currents are divergenceless, so where the gradient of the perpendicular current is non-vanishing, a non-vanishing parallel or field-aligned current must arise. (Here perpendicular and parallel are directions relative to the magnetic field.) A field-aligned current was identified in the first Mercury flyby in conjunction with substorm activity (see Fig. 19.2). Computer simulations reveal Chapman–Ferraro currents on Ganymede's magnetopause and parallel currents flowing along the field towards and away from Jupiter's ionosphere. The existence of an aurora provides additional reason to believe that such currents are present. A puzzle then arises. How do these currents close? Atmospheres for both bodies are probably time-varying and patchy, so the existence of a gravitationally bound ionosphere is unlikely. Ions produced from the clouds of newly ionized neutrals that are sputtered off the surfaces, referred to as pickup ions, can carry current across the field and may be implicated in current closure and some attention has been paid to the possibility of current closure through the surfaces. However, neither the conducting paths through which field-aligned currents close nor the effect on the dynamics of the system of the current closure paths are fully understood. There is much more to be learned about how magnetospheres work by studying these two small systems.

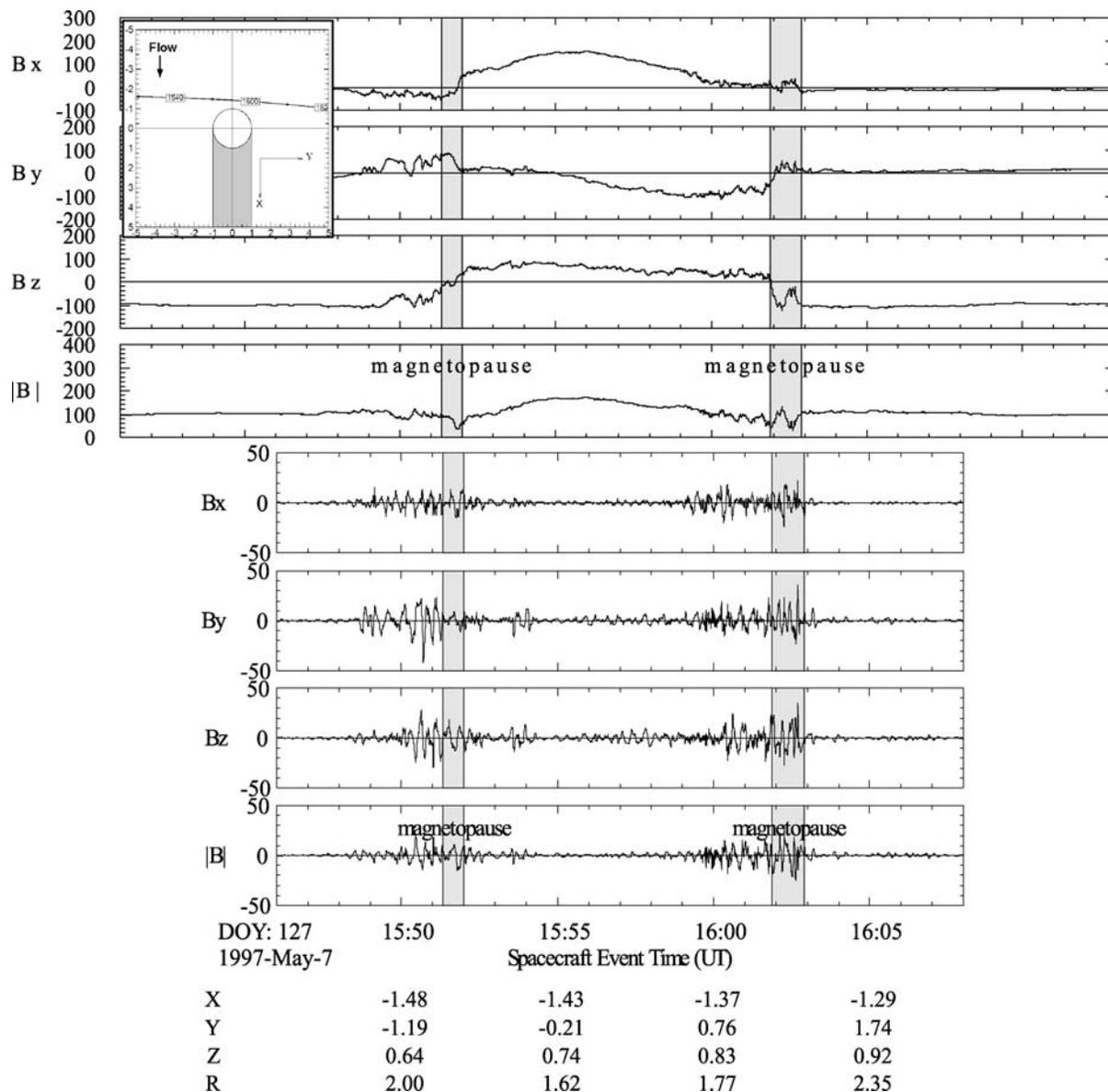


Fig. 19.6. Magnetic field data from a pass on May 7, 1997 in the upstream region of Ganymede's magnetosphere. *Above:* The magnetic field magnitude and components in a coordinate system defined by the flow (x -direction) and the background field direction (in the x - z plane). *Below:* detrended data revealing large amplitude waves near the magnetopause crossings. *Inset* shows the projection of the trajectory on the equatorial plane of the magnetosphere with the wake region shaded

19.3.2 Giant Magnetospheres of Rapidly Rotating Planets

The giant magnetospheres of the solar system are those of Jupiter and Saturn. Descriptions of Jupiter require a vocabulary rich in superlatives (see Bagenal et al.,

2004). In scale, Jupiter dwarfs the other planets of the solar system. It has the largest mass, spins fastest around its axis, and has the largest magnetic moment. It seems natural that it should also have the largest magnetosphere. It will become clear that additional

unique features relate to dominant role of rotational acceleration, the relatively low momentum density of the solar wind at Jupiter's orbit, and the importance of the four large Galilean moons as plasma sources.

Jupiter – the First Discoveries

Decimetric radiation. For Jupiter, the existence of a magnetic field was inferred in the 1950s from the properties of radio emissions at decimetric wavelengths (tenths of centimeters wavelength or GHz frequency). The radiation is polarized roughly transverse to Jupiter's spin axis in a plane that rocks up and down by about $\pm 10^\circ$ every Jupiter rotation. The emissions are explained as synchrotron radiation from energetic electrons gyrating near the equatorial plane of a dipolar field. The observed rocking of the plane of polarization was used to infer (correctly) that Jupiter's dipole moment is tilted by about 10° from the spin axis. However, the decimetric radiation gives no information on the magnitude of the field.

Decametric radiation and Io control. The missing information regarding field magnitude was provided from analysis of the very intense decametric emissions (tens of meters wavelength or \sim tens of MHz frequency) modulated at roughly the spin period. The periodicity of this radiation corresponds to the rotation period of the internal magnetic field and, in the absence of a solid surface, is used to define the rotation rate of Jupiter.

Decametric radiation at Jupiter is emitted at the gyrofrequency (f_g) of electrons moving in near circular orbits perpendicular to the magnetic field. Here

$$f_g = qB/2\pi m \quad (19.5)$$

where q is the charge, B is the field magnitude, and m is the particle mass, so, by measuring the frequency, one determines the field magnitude in the source region. A cutoff at the high frequency end corresponds to emission from the region where the magnetic field reaches its largest value, just above the atmosphere of Jupiter. The observed cutoff implies a surface field of ~ 0.001 T. Direct spacecraft measurements revealed that Jupiter's dipole field intensity is 0.0004 T at the equator and several times larger near the pole, providing confirmation of the early estimates. With such a large field (more than ten times the maximum dipole field strength at Earth's

surface), there was no doubt that Jupiter would have a magnetosphere; the low solar wind density expected at Jupiter's orbit suggested that its boundary, the magnetopause, would be very distant from Jupiter's cloud tops. Estimates placed the subsolar point at a distance near $50 R_J$ ($R_J \equiv$ Jupiter radius = 74,000 km) and in situ measurements show that this estimate gives a rough lower bound to the magnetopause location.

Decametric emissions revealed yet another aspect of Jupiter's magnetosphere before the first spacecraft measurements became available. The intensity of the radiation is controlled by the orbital location of the closest large moon, Io, relative to the Earth-Jupiter line, providing the first hint that Io is important to phenomena occurring in Jupiter's magnetosphere.

Neutral clouds of sodium and sulfur ions. In 1973, ground-based observations uncovered yet another surprise. Again the discovery was related to Io, which was found to move around its orbit enshrouded in a cloud of neutral sodium. Sodium turns out to be a marker of the many different neutral species that are liberated from Io into Jupiter's magnetosphere and following the detection of the sodium cloud, ionized sulfur was also observed remotely near Io's orbit.

Spacecraft exploration. Shortly after the discovery of the sodium cloud, Pioneer 10 became the first spacecraft to probe the magnetosphere of Jupiter. Within a few years, direct spacecraft measurements (by Pioneers 10 and 11 and Voyager 1 and 2) confirmed the basic interpretation of the remote observations and uncovered new information. The magnetosphere is even bigger than initial estimates had suggested. Its size can change rapidly. A torus of heavy ions and electrons stretches outward from the orbit of Io. The shape of Jupiter's magnetosphere is flatter than Earth's. Intense fluxes of energetic charged particles fill much of the interior. Exploration continued with an encounter by Ulysses as it swung around Jupiter on its way to a pass over the pole of the sun. As the century drew to a close, Galileo became the first spacecraft to go into orbit around one of the giant planets. Not only did this orbiting spacecraft explore regions never previously encountered, but also it remained within the magnetosphere long enough to reveal the variability of the system over months to years and to investigate the dynamical processes that contribute to the transport of mass and momentum within the magnetosphere.

Structure of Jupiter's Magnetosphere

The particles that populate Earth's magnetosphere come either from the ionosphere or from the solar wind. At Jupiter, such sources are also present, but their contributions are small compared with the sources introduced by ionization of neutrals from the Galilean moons. A useful estimate is that Io injects one ton of plasma per second into its environment. Other moons are weaker sources of neutrals and of the ions formed from them, but their production rates are not negligible.

The heavy ion plasma introduced in the vicinity of the moons controls much of the magnetospheric structure as can be understood by considering the forces that act upon the plasma. The physics of the system is largely described in MHD terms, i.e., in terms of a theory that combines the laws of fluid motion with those of electromagnetic theory. Let us focus on two useful equations:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mathbf{j} \times \mathbf{B} + \text{inertial forces} \quad (19.6)$$

$$\mathbf{j}/\sigma = \mathbf{E} + \mathbf{u} \times \mathbf{B} \text{ and if } \sigma \rightarrow \infty, \quad \mathbf{E} + \mathbf{u} \times \mathbf{B} = 0 \quad (19.7)$$

(in SI units) where (19.6) shows how forces accelerate the plasma and (19.7) is Ohm's law for an electrically conducting fluid in motion. Here ρ is the mass density, \mathbf{u} is the fluid flow velocity, p is the thermal pressure, \mathbf{j} is the electrical current density, \mathbf{B} is the magnetic intensity, \mathbf{E} is the electric field and σ is the electrical conductivity. In most magnetospheric applications, one may assume that the plasma conductivity is infinite and adopt the second form of (19.7). In this limit, there is a direct correspondence between the flow and the electric field.

The plasma of the magnetosphere is linked by the magnetic field to Jupiter's ionosphere (period ~ 10 h). Over much of the magnetosphere, field-aligned currents link the magnetospheric plasma with the ionospheric plasma, closing through the equatorial plasma to exert a $\mathbf{j} \times \mathbf{B}$ force directed in the sense of Jupiter's rotational motion. The plasma is said to corotate if its angular velocity is that of Jupiter; in the inner magnetosphere the flow is close to corotational. In the middle magnetosphere, corotation is not fully imposed, in which case one talks of corotation lag.

In the rotating system, inertial forces are the inward force of gravity and the outward centrifugal force of the corotating plasma. Beyond a few R_J the gravitational

force is negligible but the outward centrifugal force becomes increasingly important with radial distance. The bulk plasma rotating within the magnetosphere experiences centrifugal acceleration, $r\omega^2$ with r the distance from Jupiter's spin axis, and ω the angular velocity of the plasma about Jupiter's spin axis, typically somewhat less than Jupiter's angular velocity.

In the equilibrium system, the centrifugal force of rotating heavy ion plasma and the pressure gradient force of energetic particles are both directed outwards. They are balanced by an inward $\mathbf{j} \times \mathbf{B}$ force exerted by a disk of azimuthal current. The effect is seen as a stretching of the field lines near the equator in the dayside region between $\sim 15 R_J$ and $\sim 50 R_J$ in Fig. 19.7, a schematic representation of a noon-midnight cut through the magnetosphere. The stretched field lines curve sharply as they cross the equator where they exert a curvature force great enough to contain the plasma.

Although many other factors are important in distinguishing the Jovian magnetosphere from others, it is the fact that centrifugal forces are comparable in importance to the other forces through much of the magnetosphere that is critical. In turn, the importance of these inertial forces can be attributed to the rapid rotation of Jupiter, its large size, and the massive amount of plasma introduced into the magnetosphere by the Galilean moons.

Magnetic configuration. Magnetospheres are often described by working inward from the solar wind, but here we shall proceed outward. This approach is natural in a system dominated by the internal sources of momentum that we have described. We start by completing an overview of the magnetic configuration. The internal planetary magnetic field imposes the structure in the inner magnetosphere, the region within $\sim 15 R_J$ of Jupiter as indicated in Fig. 19.7. At the surface in the northern polar regions, the tilted dipole field points outward from the planet (opposite to Earth's field). Near the equator, the field is oriented southward. Close to the planet, the dipolar field is modified by contributions from higher order multipole moments. Their effect decreases rapidly with distance.

On the day side beyond the orbit of Io (between $\sim 15 R_J$ and $\sim 50 R_J$ where heavy ion plasma modifies the magnetic structure as described above), lies a disk-like plasma sheet at all local times in a region referred to as the middle magnetosphere. Beyond $\sim 50 R_J$ in the outer

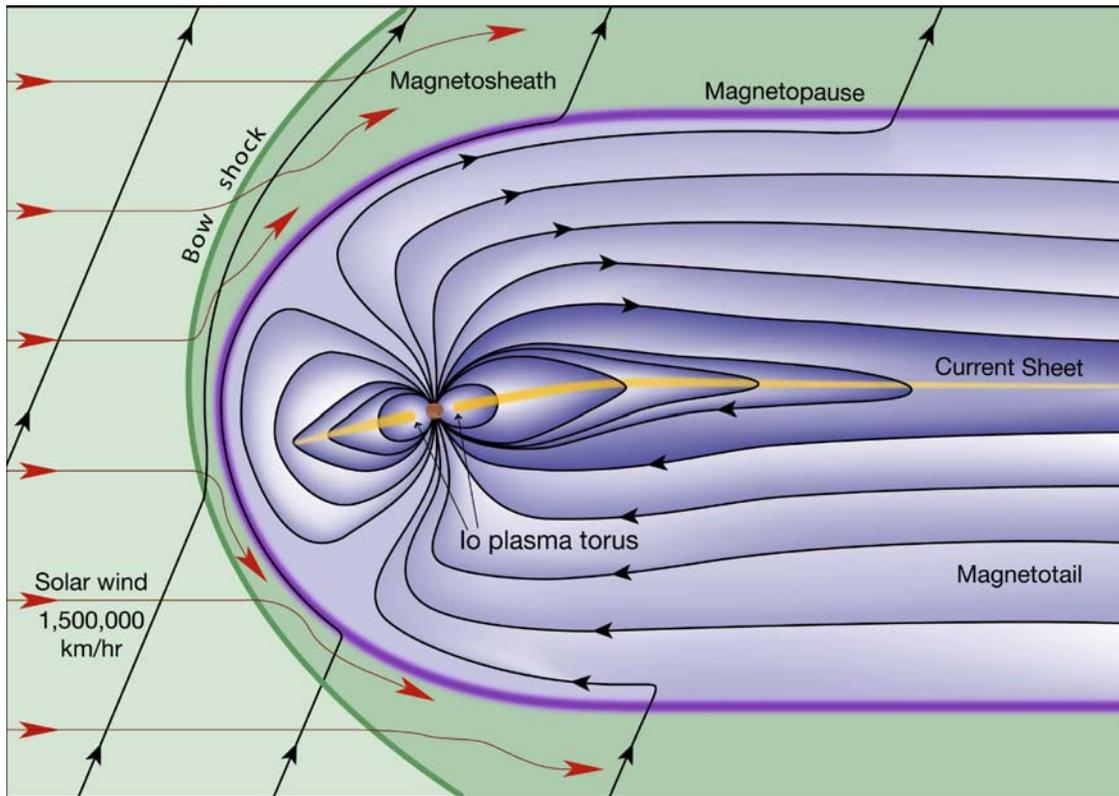


Fig. 19.7. Schematic of the Jovian magnetosphere showing the distended field lines of both day and night side magnetospheres that require an azimuthal current (gold) to flow in the minimum field region. (Courtesy of F. Bagenal, 2004.)

magnetosphere, the field lines no longer stretch radially away from the planet. On the day side of the planet, their orientation is on average roughly dipolar, with southward orientation dominating near the equatorial plane. The field in this region is very disordered and fluctuations of large amplitude are typical. On the night side, the disk-like structure persists to much larger distances. The field structure is similar to that of Earth's magnetotail, although the data are still inadequate to specify the nightside configuration fully.

The magnetopause location is extremely variable. The observed distances to the subsolar region of the magnetopause range from less than $50 R_J$ to more than $100 R_J$, a set of distances that can be consistently understood in terms of pressure balance arguments. The heavy ion plasma spinning around the planet at a fraction of the rate of planetary rotation reduces the gradient of total pressure in Jupiter's dayside magnetosphere relative to that of a vacuum dipole field. Changes

of solar wind dynamic pressure that produce a displacement of some fraction of the distance to the nose of the magnetopause at Earth produce a much larger fractional displacement of the magnetopause at Jupiter.

Beyond the magnetopause is found the shocked solar wind plasma of the magnetosheath, bounded, as at Earth, by a bow shock that stands sunward of the magnetosphere in the solar wind. The bow shock slows the solar wind and diverts its flow from the antisolar direction. The standoff distance between the magnetopause and the bow shock is smaller than predicted by simple scaling of the standoff distance observed at Earth. The reduction is, however, consistent with expectations for a magnetosphere somewhat flattened in the north-south direction relative to the roughly circular transverse cross section of Earth's magnetosphere. That distortion of the magnetospheric shape is consistent with the radially extended structure of the magnetic field through much of the magnetosphere.

Plasma sources and characteristics. As at Earth, the ionosphere and the solar wind supply some of the magnetospheric ions at Jupiter. Ions from these sources are predominantly protons. The sources of the heavy ions are the Galilean moons. Clouds of neutrals, sputtered off the atmospheres and surfaces by impacts of charged particles, surround these moons. As was already apparent from ground-based observations, the dominant source is Io. Several processes including photoionization, impact ionization, and charge exchange ionize the neutrals, and thereby create a heavy ion plasma in the equatorial portion of the inner magnetosphere.

Consider a neutral initially at rest with respect to one of the moons. Beyond $\sim 2 R_J$, the speed of corotation exceeds the Keplerian speed and plasma flows onto the trailing sides of the moons at relative speeds that increase with distance from Jupiter. Ionization of a neutral produces an ion–electron pair at rest in the moon’s frame and embedded within the flowing plasma. The newly added ions (called pickup ions) and electrons extract momentum as they are accelerated up to the local flow speed. This slows the plasma. If the plasma near the equator flows more slowly than the plasma off the equator, magnetic flux tubes twist out of meridian planes. The twist, referred to as bendback or corotation lag, implies $\partial B_\phi / \partial \theta < 0$. This inequality implies the presence of an outward-directed radial current density (j_r) and an associated Lorentz force that accelerates the slowed flow. The current circuit closes through field-aligned currents that couple the equatorial plasma to Jupiter’s ionosphere and extract momentum from its rotation. This type of field distortion and the associated coupling between the equatorial regions and Jupiter’s ionosphere develops wherever the plasma is not fully corotating.

Through much of the magnetosphere, the density is dominated by the low energy (~ 100 eV ions) plasma but the pressure is dominated by energetic ions with energies above ~ 10 keV. From Io’s orbit out to $\sim 50 R_J$, the low energy plasma is confined to a disk of $\sim 1 R_J$ north-south thickness. The confinement is another manifestation of the importance of the centrifugal force. The field-aligned component of the latter force is directed towards the centrifugal equator, the point on the field line that lies farthest from the spin axis. More thorough analysis shows that within about $20 R_J$, the plasma density is highest at a position between the centrifugal equator and the magnetic equator and that the peak density shifts to-

wards the magnetic equator beyond $20 R_J$. The plasma density decreases with distance along the flux tube with a scale height of order $1 R_J$.

Plasma transport and losses. On a long time scale, plasma sources must balance plasma losses. Several loss mechanisms for magnetospheric plasma exist. Interchange motion is generally thought to be the principal process that transports heavy ion plasma from the source at Io outward through the middle magnetosphere. (The loss of plasma in the outer magnetosphere is discussed in Sect. 19.3.2.) Because magnetic flux must be conserved, when one flux tube moves out, another flux tube moves in to replace it. In an interchange motion, the exchange involves entire flux tubes with their associated plasma. In the approximately corotating plasma torus, interchange occurs spontaneously because the outward displacement of loaded flux tubes accompanied by the inward displacement of depleted flux tubes reduces the free energy of the system. (The distinction between loaded and depleted is based on the total plasma mass contained in the flux tube.)

The interchange model has been hard to confirm by observations, leading some to suggest alternative transport mechanisms. Nonetheless, there is evidence that interchange occurs. Voyager’s plasma wave measurements found signatures consistent with intermingled low and high-density flux tubes in the middle magnetosphere. The Galileo Orbiter provided compelling evidence that adjacent flux tubes can have very different plasma content. Small flux tubes (probably of order 1000 km across) with low density plasma at high pressure were detected in a background of higher density, lower pressure plasma just beyond Io’s orbit. It is not yet clear whether the distribution of interchanging flux tubes is ordered relative to Jupiter’s surface, Io’s location, or local time or occurs randomly. The shape of the equatorial cross sections of interchanging flux tubes remains uncertain. Proposed forms include irregular “blobs” and radial fingers of outward and inward moving flux.

Evidence for interchange has also been found at Saturn, where, as at Jupiter, centrifugal stress is important. At Earth, the outer plasmasphere can become unstable to interchange if it extends beyond geostationary orbit. The theoretical arguments were first expounded in the 1980s and good evidence of small scale interchanging flux tubes was found in the Cassini earth-flyby data two decades later.

The properties of the heavy ion plasma at Jupiter are also affected by the process of charge exchange in which a neutral particle becomes ionized and loses an electron to an ion of the plasma. The newly formed ion is accelerated by the convection electric field to the flow velocity of the background plasma and acquires thermal speed equal to that flow speed. The process does not change the charge density of the plasma but, depending on the thermal energy of the original ion, the process may cool or heat the plasma. The newly formed neutral atom retains the velocity of the original ion, which is close to corotation velocity. Lacking a charge, it is unaffected by the magnetic field and escapes from the system on an almost linear path. Neutral matter is thereby distributed in an extended disk surrounding Jupiter. The neutral sodium halo, spread over distances of order $500 R_J$ near Jupiter, has been observed from Earth.

Twist and warp of the equatorial current sheet. In the schematic of Fig. 19.7, the distended field lines, stretched radially outward by the torus of heavy ions, appear to lie in meridian planes and to be symmetric about a current sheet in the magnetic equatorial plane which is the center of the plasma torus. The actual current sheet surface is warped, and field lines twist out of meridian planes. One might think that the forces associated with the twisted field configuration would ultimately accelerate the plasma to corotational speed and that the twist would disappear. Yet bendback persists. One reason is that pickup is not confined to the immediate vicinity of the moons but occurs throughout the plasma torus, extracting momentum from and slowing the flow, predominantly in the near-equatorial regions. Another reason is that the interchange of flux tubes or other radial diffusion processes transport the bulk plasma radially outward. If plasma moving outward conserves angular momentum, it begins to lag corotation. Again the lag is largest near the equator, causing the field to bend back.

Contributing to the warping of the current sheet is an additional effect related to the north-south motion of Jupiter's magnetic equator relative to points on the rotational equator. As Jupiter spins, the magnetic equator at its surface rocks up and down; associated field perturbations are carried outward from the surface of Jupiter by Alfvén waves whose finite propagation speed introduces a distance-dependent lag to the response. The current sheet appears wavy in meridian planes and the surface appears warped.

Energetic particles: sources, transport and losses. It is customary to regard particles in the >10 keV range as energetic particles. At Jupiter, the energetic ions include protons and a large fraction of heavy ions; energies extend into the tens of MeV per nucleon range. Typically the energetic particle flux decreases with energy according to a power law. Within the magnetosphere, even for protons the energies are far higher than expected for direct acceleration of solar wind particles. Pickup of heavy ions from neutrals does not produce energetic particles.

How then are energetic ions produced? The mechanisms responsible for accelerating ions to energies at which they are observed are not fully established even in the case of Earth's radiation belts. It is known that particles gain energy as they move spatially inward along a gradient of magnetic field magnitude because, in the particle's frame, the magnetic field is increasing in time. If the motion is slow, they conserve the quantity

$$\mu = W_{\perp} / B \text{ where } W_{\perp} = \frac{1}{2} m v_{\perp}^2 \quad (19.8)$$

μ is referred to as the first adiabatic invariant. Here W_{\perp} is the kinetic energy associated with motion perpendicular to the magnetic field and v_{\perp} is the magnitude of the perpendicular velocity of a particle. Inward displacement into an increasingly strong magnetic field increases a particle's energy, but even displacement from the magnetopause to the inner magnetosphere can explain only the low energy end of the energetic particle spectrum. The heavy ions pose an even more serious dilemma because their source is in the high field region and adiabatic outward displacement will cause them to lose, not gain, energy.

Some explanations of the acceleration process at Jupiter have been proposed. Two involve recycling. In order to understand how recycling works, one needs to consider how charged particles move in a magnetic field. Projected into planes perpendicular to the local field, the particles gyrate with the perpendicular velocity v_{\perp} around a magnetic field line as the gyration center slowly drifts. The radius of the circular orbit centered at the gyration center is referred to as the gyroradius, ρ_g , where

$$\rho_g = |v_{\perp}| / 2\pi f_g. \quad (19.9)$$

Along the magnetic field, particles move with a parallel velocity $v_{\parallel} = v - v_{\perp}$ where v is the total velocity. A stationary magnetic field does not affect the total energy

of the particle and hence $|\mathbf{v}|$ cannot change but the ratio of $|\mathbf{v}_\perp|$ to $|\mathbf{v}_\parallel|$ and correspondingly the pitch angle $\alpha = \tan^{-1}(|\mathbf{v}_\perp|/|\mathbf{v}_\parallel|)$ can change. As a particle moves off the equator, the field increases in magnitude and $|\mathbf{v}_\perp|$ increases to satisfy (19.8). Necessarily $|\mathbf{v}_\parallel|$ decreases. When $|\mathbf{v}_\parallel| = 0$, $|\mathbf{v}_\perp|$ is the total speed. At this point, the particle starts back to the equator. The location where the reversal of $|\mathbf{v}_\parallel|$ occurs on a field line, the place where its bounce motion takes it farthest from the equator, is called the mirror point of the particle motion. One recycling model supposes that ions move in from the magnetopause, gaining energy as they move into the stronger field. Having gained energy on their inward path, ions near their mirror points are scattered across field lines by interaction with waves. Recalling that the field lines of a dipole field come close together as they approach the pole, one sees that even short scattering distances across field lines close to the ionosphere can displace an ion onto a field line that returns to the equator far from the initial field line. If the scattering process is sufficiently fast, (19.8) does not apply, and the ions arrive at the equatorial point of the new field line with some of the energy that they acquired on their inward pass. They gain additional energy on their next inward displacement and repeat the scattering process. Several repetitions of such a cycle can, in principle, accelerate particles to the high energies observed.

The model described above was designed principally to account for the acceleration of ions from the solar wind, ions whose source region is the outer magnetosphere. However, molecular ions from Jupiter's ionosphere and heavy ions from the satellites account for roughly half of the energetic ion population. For heavy ions, a different recycling model has been developed. Here one considers the fate of a neutral atom produced by charge exchange. As described previously, such neutrals move away from Jupiter at high speed. There is a small but finite probability that the neutral will be re-ionized before leaving the magnetosphere. If so, $|\mathbf{v}_\perp|$ of the pickup ion will correspond approximately to the local rotation speed of the plasma, and in the outer magnetosphere the ion energy can be several keV. Again (19.8) may be used to argue that if this new heavy ion moves closer to Jupiter, it will gain energy in proportion to the increase of B . It is not clear that this process can account fully for the observed particle energy spectra, but it does partially account for the pres-

ence of energetic heavy ions. At Earth, some models for energetic particle acceleration invoke electromagnetic wave interactions that can scatter particles in energy. Such processes may also contribute to the acceleration of particles in other magnetospheres.

Transport of energetic particles is similar in some ways to transport of low energy particles. Through the inner magnetosphere and middle magnetosphere, energetic particles typically move azimuthally around Jupiter as does the corotating low energy plasma. The azimuthal velocity of energetic particles differs slightly from that of low energy particles because energetic particles also experience a non-negligible magnetic field gradient drift. Ions drift faster than corotation and electrons drift more slowly. In addition, energetic particles participate in flux tube interchange described previously with the energetic particle flux highest on the low density, inward-moving flux tubes. In the outer magnetosphere, there is a strong local time element in transport. Independent of energy, particle flow down the tail is an effective loss process.

In the discussion of particle acceleration, radial transport was invoked. Radial transport arises partly through stochastic fluctuations. If inward transport and outward transport are equally probable, the effect of random motion is to spread the distribution away from its peak value. Protons introduced into the outer magnetosphere from the solar wind are carried inward by radial diffusion while flux tubes plentifully loaded with low energy heavy ions are transported radially outward from Io's orbit in the inner magnetosphere. Interchange motion, a driven motion that is not stochastic, dominates diffusion outside of the orbit of Io, but this is not the case inside the orbit of Io. Thus, transport inward from Io's orbit proceeds slowly, driven by fluctuations imposed by winds at the feet of the flux tubes in Jupiter's ionosphere.

Energetic ions moving inward can be lost as a result of pitch angle scattering. In this process, interaction with plasma waves can decrease (towards 0°) or increase (towards 180°) a particle's pitch angle. Particles whose velocities are nearly aligned with the magnetic field do not mirror before they enter the atmosphere of Jupiter where they interact with neutrals. Within the atmosphere, particles are either neutralized or lose energy through collisions. Close to Jupiter, loss occurs as particles in the near-equatorial regions collide with the neutral exosphere of Jupiter.

Dynamics of Jupiter's Magnetosphere

Flow bursts in the tail provide a loss mechanism for the Jovian plasma. Arguments in Sect. 19.2 suggest that processes driven by reconnection with the solar wind magnetic field are likely to be unimportant at Jupiter relative to the processes driven by centrifugal stresses. Unlike Earth's magnetosphere in which tail reconnection returns magnetic flux to the solar wind and accelerates solar wind plasma earthward, Jupiter's magnetotail must provide a channel for release of Iogenic plasma with little return of magnetic flux to the solar wind. In considering how plasma containment breaks down in the magnetotail, one needs to recognize that the equatorial portions of the outermost flux tubes move out substantially as the plasma rotates from noon through dusk and into the night sector. The rate of rotation is comparable with the bounce times of particles of energy less than 1 keV, and particles moving outward as they circulate into the magnetotail gain energy from the centrifugal pseudo-potential. It can be shown that this effect results in anisotropy with p_{\parallel} becoming larger than p_{\perp} . Pressure gradient and Lorentz forces can counter the centrifugal forces acting on the rotating plasma in the inner and middle magnetosphere. In the middle magnetosphere, the inward force exerted by magnetic field curvature constrains the plasma of the plasma disk. Farther out, where $p_{\parallel} - p_{\perp} - B^2/\mu_0 > 0$, the plasma-field configuration becomes unstable to the firehose instability. In the magnetotail, it seems likely that the instability becomes explosive and bubbles of plasma surrounded by magnetic field blow off down the tail. The bubbles of plasma are thought to stream down the tail as indicated schematically in Fig. 19.8. High speed outflow in the post-midnight magnetotail was first observed in Voyager energetic particles and subsequently found on multiple passes of Galileo. The outflow is analogous to that found in Earth's magnetotail where bubbles of plasma (plasmoids or flux ropes), confined by wound-up magnetic fields, form during substorms and are returned to the solar wind following acceleration down the tail, but it seems probable that Jupiter's dynamics are driven by the internal instability discussed here and that the flows are not linked to the solar wind magnetic field orientation as they are at Earth.

At Jupiter, newly injected energetic particles have been observed in the inner magnetosphere arriving with a clear energy-dependent dispersion. The dispersion

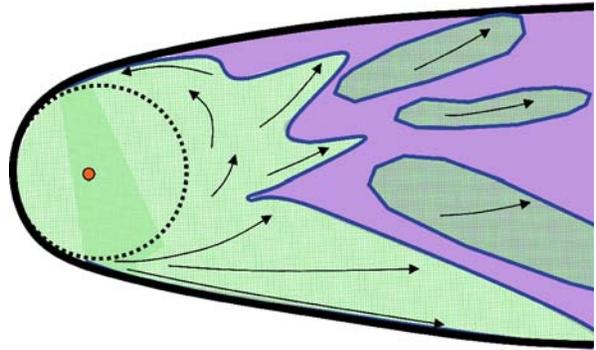


Fig. 19.8. Schematic of flow in Jupiter's equatorial magnetotail (Kivelson and Southwood, 2005)

is consistent with drift from a localized source remote from the spacecraft, the energy-dependence of the drift velocity accounting for the dispersion of arrival times. There seems not to be a preferred local time for the source location and the process is not well understood.

Energetic electrons (> 100 keV) lost from Jupiter's magnetosphere can be identified in the solar wind where measurements show that the high energy electron flux decreases with distance from Jupiter and its amplitude is modulated at the ten-hour periodicity of Jupiter's rotation. The spectral index (ratio of flux in adjacent energy channels) of MeV electrons varies with a 10 h period even at distances of order 1 AU from Jupiter.

Jupiter's Aurora

Jupiter's aurora provides visible evidence of the dynamics of the magnetosphere. As seen in Fig. 19.9, the form of the aurora differs markedly from that found at Earth where the most intense emissions are intermittent and are localized on the night side at latitudes just equatorward of the open-closed field line boundaries. At Jupiter, strong emissions are seen at latitudes substantially lower than the open-closed field line boundary in a region that forms a distorted oval about the pole. Emissions are intense at all local times in this region referred to as the main oval and do not change dramatically with universal time. Magnetic mapping indicates that the main oval is produced in regions linked to the middle magnetosphere, a region in which significant field-aligned currents arise by mechanisms described earlier in this paper. It is widely accepted that field-aligned electric fields arise where the currents link

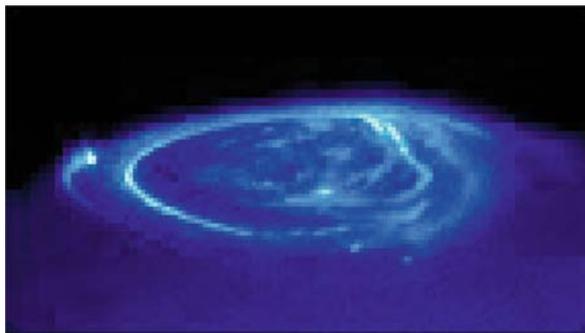


Fig. 19.9. Jupiter's northern aurora imaged by the Hubble Space Telescope (Clarke et al., 1998). The *ring-like bright feature* is referred to as the main oval and *maps* to the plasma disk in the middle magnetosphere. The *isolated bright spots at lower latitudes map* magnetically to the positions of the moons Io, Ganymede and Europa (*left to right*). The region of low emission poleward of the main oval maps to the morning sector of the magnetosphere

to Jupiter's ionosphere and that electrons accelerated by such fields excite the observed radiation. Emissions at higher latitudes are time-variable and tend to concentrate in the dusk sector of the polar ionosphere. They are most likely driven by currents that develop to maintain rotational motion as plasma moves outward between noon and dusk and on to the night side of the planet.

Of particular interest are the auroral glows present at the locations where the magnetic field links the Galilean moons to the ionospheres both north and south. These localized bright spots result from field-aligned currents that flow from the conducting bodies through the Jovian plasma that surrounds them. The field aligned current linking Io with the ionosphere is the source of the decametric emissions previously described. The ionospheric footprint of Io extends into a long trail of emission along the locus of magnetic field lines linked to Io's orbit, suggesting that restoring corotation in plasma that has slowed near Io requires a significant fraction of a Jovian rotation period.

Saturn's Magnetosphere

Saturn is similar to Jupiter in many significant ways. Its radius is 84% that of Jupiter and its rotation rate differs little. Moons and rings provide major sources of heavy ion plasma, which are spun up to near corotation by coupling to the ionosphere. The rapid rotation stretches

flux tubes radially and a plasma disk is often observed on the day side as well as the night side of the magnetosphere. Saturn's magnetosphere has been explored by Pioneer 11, Voyagers 1 and 2 and is at present being investigated more completely by the Cassini orbiter. Initial reports were published in *Nature* (433, 17, Feb 2005) and *Science* (307, 125, Feb 2005) and new results have appeared regularly since that time.

Saturn is unique in the extent of the ring system (Jupiter has only a very tenuous ring) and the number of reasonably large moons within its magnetosphere. Both rings and moons are plasma sources. The near-equatorial plasma density rises abruptly just at the outer edge of the A ring and then decreases with distance from Saturn. An extended neutral component is reported to be comparable in density to the plasma in much of the magnetosphere. Until Cassini reached Saturn, it was thought that Titan, the largest moon and one with a dense atmosphere, was a dominant source of magnetospheric ions. However, the surprising discovery of a water plume (Dougherty et al. 2006) at the tiny moon, Enceladus, has led to the recognition that the smaller moons and the rings, which provide ions derived from water ice, actually dominate the plasma sources.

Saturn's surface magnetic field is substantially smaller than Jupiter's and correspondingly its magnetosphere is substantially smaller, its sunward extent being comparable with the distance between Jupiter and the inner edge of the Jovian plasma sheet (see Fig. 19.7). This means that rotational acceleration must be considered but does not dominate at Saturn as it does in the middle and outer parts of Jupiter's magnetosphere. It is not yet established whether there are substorms at Saturn or if there is some rotation-driven mechanism for losing plasma or if multiple processes contribute to plasma losses.

Saturn's moons are not only sources but also sinks for energetic particles. Some of the plasma that flows towards a moon encounters its atmosphere or its surface and is removed from the flow. The remainder of the plasma diverts around the moon and closes in its wake, much as water in a stream parts to flow around a rock. The interaction of energetic ions with a moon may differ greatly from that of a fluid because it depends on pitch angle, bounce phase, and thermal energy. At Saturn, with the moons in the magnetic equa-

tor, particles with 90° equatorial pitch angle are strongly absorbed, but energetic particles with pitch angles near 0° or 180° move long distances along the flux tube in the time required to flow across the moon's diameter. Depending on bounce phase, they may or may not encounter the moon as their projected gyrocenters move across the moon's surface. Because very energetic particles have large gyroradii (see (19.9)), their trajectories near the moon may intersect the moon even when their gyrocenters lie pass far from the moon's surface. Thus, the cross section for loss can greatly exceed a circle with the diameter of the moon.

Energetic electrons have small gyroradii even near the outer moons, but their large v_{\parallel} implies that they bounce many times as the plasma flows across the moon. Thus, a moon's near wake is void of energetic electrons.

The voids in electron fluxes and the minima in ion fluxes just downstream of a moon are referred to as microsignatures of the moon. Detailed analysis of the energy and pitch angle dependent microsignatures is useful for the analysis of the magnetic field and gives insight into the nature of the interaction with the moon. The particle depletion in the immediate wake of a moon fills in through radial diffusion at increasing azimuthal distance from a moon. The variation with downstream distance can be used to infer the radial diffusion rate for the energetic particles. In the steady state, the rates are inferred from the slope of the distributions of particles with fixed adiabatic invariants. The solution relies heavily on knowledge of sources and sinks. In a microsignature, one knows precisely when and where the dropout of flux was produced and how long it has taken the plasma to reach the spacecraft. With this information, diffusion coefficients and rates are more accurately established. The inferred diffusion rates roughly agree with the rates determined in other ways. Where there are discrepancies, one must not immediately assume that the rates inferred from microsignatures are pertinent more generally because the plasma conditions may be atypical in the immediate vicinity of a moon.

Like Jupiter and Earth, Saturn's aurora instructs us on aspects of ionosphere-magnetosphere coupling. Saturn's auroral emissions are localized at rather high latitudes and appear to link to the outer boundary of the magnetosphere where they are likely to reflect acceleration associated with reconnection.

Saturn's magnetic dipole moment is closely aligned with the spin axis, so, in contrast with Jupiter, its plasma sheet does not flap up and down as the planet rotates. Despite the axial symmetry of the magnetic field, variations of the magnetic field and the charged particle fluxes at the planetary spin period of 10.7 h are persistent at all locations in the magnetosphere. The periodicity was first identified in the radio wave spectra. Like Jupiter, Saturn emits radio waves modulated at approximately the planetary spin period but, because the radiation is emitted near the electron cyclotron frequency at relatively low altitude and Saturn's dipole field at the surface is weaker than Jupiter's, the modulated emissions are in the kilometric band rather than the decametric band. The periodic modulation is somewhat puzzling because in the absence of dipole tilt there is no clear explanation for the varying intensity; however, high order magnetic multipoles that cannot be ruled out by observations may introduce azimuthal asymmetry at low altitudes. Another puzzle is that the observed period changes over time, having increased by about 6 min between 1980–81 when it was identified by Voyager and 2004–2005 when it was again measured by Cassini. Variable periods were found by Ulysses in the intervening years and there is some recent evidence that the period is increasing systematically with universal time (personal communication: A. Lecacheux, 2006). A close correlation is found at Saturn between rotation-averages of the intensity of kilometric radiation and the integrated auroral input power. Kilometric radiation from Earth's auroral ionosphere (known as auroral kilometric radiation or AKR) is also known to correlate with auroral activity.

Variations of the magnetospheric magnetic field at the period of planetary rotation were discovered in the Voyager data by Espinosa and Dougherty (2000). They interpreted the spin period modulation as a signature of radial transport mechanically imposed at an azimuthally localized region close to the planet. Although signs of periodicity were subtle in the flyby data of the first spacecraft to encounter Saturn, spin period modulation of particles and fields properties is dramatically evident in the data acquired by Cassini on its orbital tour. Localized enhancements of energetic particle flux appear periodically on the night side of the planet and rotate around the planet. The magnetic field amplitude and orientation varies with a 10.7 h period. The relative phases of radial and azimuthal field components follow the pattern that would be imposed by a two cell convective flow pattern

that rotates with the planet inside of $\sim 15 R_S$ (R_S is the radius of Saturn = 60,278 km) and expands or contracts radially beyond that distance.

19.3.3 Unclassified Magnetospheres

The magnetospheres referred to as unclassified are those of Uranus and Neptune. Bagenal (1992) gives insightful descriptions of their unusual properties. These magnetospheres are comparable in scale to Saturn's. Radio emissions, detected as Voyager approached Uranus in 1981, provided the first suggestion that Uranus did have a magnetosphere.

The special character of these systems is linked to the large angles between the planetary dipole axis and the spin axis (see Table 19.1) as well as the presence of strong higher order multipoles of the internal magnetic field. In one rotation period, their magnetospheric configurations vary markedly as the angle between the planetary field and the solar wind velocity changes. The magnetospheres that arise in this case are highly asymmetric and vary greatly in structure at the period of planetary rotation (see Fig. 19.10). The plasma density remains low because of the unstable structure of the magnetosphere.

The configuration of Uranus' magnetosphere also changes in important ways as the planet moves around the sun because the planet spins around an axis that lies only 8° out of the orbital plane. At the time of Voyager's flyby in 1981, the spin axis was nearly aligned with the solar wind flow. In this unique alignment, the flow imposed by planetary rotation is nearly orthogonal to the flow imposed by magnetic reconnection with the solar wind. A magnetotail develops, with two lobes separated by a current-carrying region of high plasma density much as at Earth, but at Uranus the structure rotates around the Uranus-Sun line at the period of planetary rotation. As illustrated in Fig. 19.10a, changing orientation propagates antisunward producing a twisted tail that can be clearly identified in simulations (Toth et al., 2004).

In the 25 years since the Voyager flybys, the planet has moved far along its orbit (84-year period) and the spin axis is now closely aligned with the direction of planetary motion; the solar wind flow is not far from orthogonal to the spin axis as is the case at Earth. The magnetospheric configuration must be much more

Earth-like. However, even in the present configuration, the large tilt of the dipole moment should continue to impose significant variability on the structure of the magnetosphere.

The spin axis of Neptune is tilted by only 29.6° to its orbital plane but the dipole axis is tilted by -47° and this configuration produces a magnetospheric structure that varies dramatically within each spin period. As illustrated in Fig. 19.10b, twists in the tail and circular tail current sheets appear in simulations (Zieger et al., 2004) and make it clear that a quasi-steady configuration capable of populating the magnetosphere with plasma is never attained. The simulations of Neptune's changing magnetospheric configuration are of particular interest because of their bearing on our understanding of possible magnetospheres that may have developed during intervals of dipolar reversals at Earth.

Primary plasma sources are moons at Neptune (analogous to Jupiter and Saturn) and the planet's ionosphere at Uranus. Energetic particles, probably accelerated through reconnection in the magnetotail, are observed in both systems, but because of the unusual magnetospheric geometry of these two systems, the energy density in such particles remains small and they do not seem to contribute a significant ring current.

19.3.4 Mars: a Special Case

Extensive exploration of Mars has, in recent years, provided insight into the plasma and field environment of this interesting planetary system (Nagy et al., 2004). Mars lacks a planetary dipole moment sufficient to form a magnetosphere, but localized crustal magnetic anomalies, widespread in the southern hemisphere, are so strongly magnetized that they must form magnetic bubbles capable of holding the solar wind off at altitudes of several hundred kilometers over regions of similar scale. The effects of these strongly magnetized regions on the ionosphere are interesting to contemplate. The magnetic bubbles must arch above the surface in forms similar to solar arcades; reports of encounters with the ionosphere at exceptionally high altitude above the regions of intense magnetic field are consistent with this expectation. Reconnection with the magnetic field of the solar wind should produce open field lines in the vicinity of the arches on the day side of the planet. On these field lines precipitating particles are likely

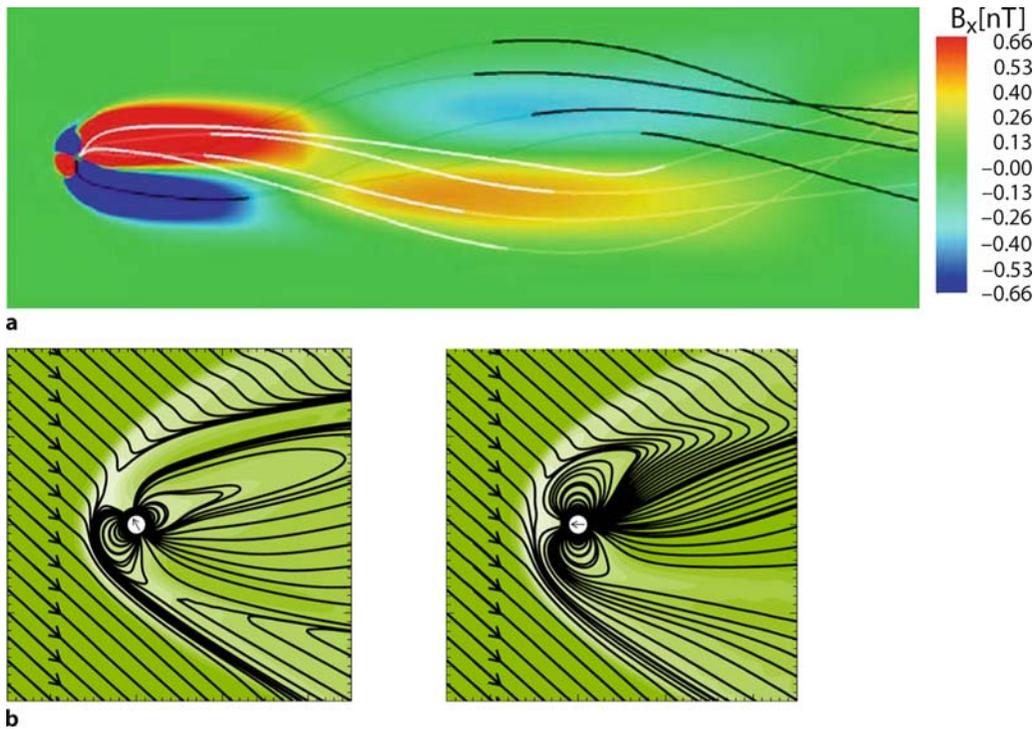


Fig. 19.10. (a) From a simulation by Toth et al. (2004). Uranus' magnetosphere with spin axis oriented as it was at the time of the Voyager flyby showing the twisted magnetic configuration of the tail. Magnetic field lines connected to the northern (*black lines*) and southern (*white lines*) poles. Colors represent the x -component of the field. The *color scale* is saturated near the planet. (b) From a simulation by Zieger et al. (2004). Diurnal variation of the magnetic field configuration and pressure in an equatorial dipolar paleomagnetosphere for dipole axis at 30° to the normal to the ecliptic plane (*left*) and at 90° (*right*). The configurations are close to those those relevant to Neptune's magnetosphere at different times during a planetary rotation period

to heat the ionosphere. It has been proposed that on the night side, magnetic shielding of the ionosphere within the closed magnetic bubbles may limit access of ionizing electrons and thus imply reduced ionospheric densities above the crustal anomalies. Although some magnetospheric phenomena occur in the regions of anomalously intense magnetic field, their limited spatial extent precludes the development of most magnetospheric phenomena, so the suggestive description of these regions as “mini-magnetospheres” is, in the view of this author, not appropriate.

19.4 Summary: some Lessons for Earth

The magnetospheres of the solar system come in many forms and sizes. By exploring the different magnetospheres we begin to appreciate that Earth's

magnetosphere may have been very different in past epochs. When the magnetic dipole reverses, its magnitude may decrease; one can conceive of times when Earth's magnetosphere resembled Mercury's, with the magnetopause lying close to the surface and can think of how this would have affected Earth. For example, at such times, energetic particles would have had ready access to the surface and radiation belts would have been evanescent. Atmospheric escape could have been enhanced. The same situation would have arisen if a magnetosphere had formed in the earliest days of solar system evolution when a T-Tauri solar wind was far more powerful than today's solar wind.

It is quite likely that during magnetic reversals the dipole moment merely rotated, possibly producing a magnetosphere that resembled the highly unstable the magnetospheres of Uranus and Neptune.

Was Earth's magnetosphere ever dominated by rotation as is Jupiter's? It seems unlikely, even though planetary rotation has slowed over the eons. But by studying Jupiter, we learn to appreciate the role of centrifugal stresses and are primed to identify their subtle effects in Earth's magnetosphere. For example, beyond geostationary orbit, the centrifugal radial stresses dominate gravitational stresses and there is some evidence that bits of the plasmasphere can be lost through a process analogous to interchange at Jupiter.

Finally, one must recognize that the magnetospheres we have encountered may be duplicated elsewhere in the galaxy in the vicinity of other stars. One must expect radio emissions, modulated fluxes of escaping particles and planetary auroras in these distant systems, possibly providing new tools for investigation of extrasolar planets.

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