13

Comparative planetary environments

FRANCES BAGENAL

13.1 Introduction

The nature of the interaction between a planetary object and the surrounding plasma depends on the properties of both the object and the plasma flow in which it is embedded. A planet with a significant internal magnetic field forms a magnetosphere that extends the planet's influence beyond its surface or cloud tops. A planetary object without a significant internal dynamo can interact with any surrounding plasma via currents induced in an electrically conducting ionosphere.

All the solar system planets are embedded in the wind that streams radially away from the Sun. The flow speed of the solar wind exceeds the speed of the fastest wave mode that can propagate in the interplanetary plasma. The interaction of the supersonic solar wind with a planetary magnetic field (either generated by an internal dynamo or induced externally) produces a bow shock upstream of the planet. Objects such as the Earth's Moon that have no appreciable atmosphere and a low-conductivity surface have minimal electrodynamic interaction with the surrounding plasma and just absorb the impinging solar wind with no upstream shock. Interactions between planetary satellites and magnetospheric plasmas are as varied as the moons themselves: Ganymede's significant dynamo produces a mini-magnetosphere within the giant magnetosphere of Jupiter; the electrodynamic interactions of magnetospheric plasma flowing past the atmospheres of volcanically active Io (Jupiter) and Enceladus (Saturn) generate substantial currents and supply more plasma to the system; moons without significant atmospheres (e.g. Callisto at Jupiter) absorb the impinging plasma. The flow within magnetospheres tends to be subsonic, so that none of these varied interactions forms a shock upstream of the moon. The types of plasma interactions are summarized in Table 13.1.

The general principles of the structure and dynamics of planetary magnetospheres were presented in Chapter 10. The physical principles and observational

Table 13.1. *Types of interactions of planets with their embedding flow*

Plasma flow	No dynamo	Dynamo
Subsonic	Io (Jupiter) Enceladus (Saturn)	Ganymede (Jupiter)
Supersonic	Venus – atmosphere Moon – no atmosphere	Earth, Mercury – slow rotation Jupiter, Saturn – fast rotation Uranus, Neptune – oblique rotation

evidence for the dynamics of the Earth's magnetosphere (e.g. Cravens, 1997; Kivelson and Russell, 1995) are discussed in Vol. II. Here we will discuss the planets within our solar system, comparing their similarities and differences. A basic introduction is given in Van Allen and Bagenal (1998). Deeper studies of comparative magnetospheres range from the abstract to the specific (Siscoe, 1979; Vasyliūnas, 1988, 2004; Kivelson, 2007; Walker and Russell, 1995; Bagenal, 1992; Russell, 2004, 2006; Kivelson and Bagenal, 2007). In this chapter we take an intermediate path, with the goal of applying the general principles of Chapter 10 to specific planets but also providing a qualitative appreciation of the different characters of our local family of magnetospheres. We shall return to plasma interactions with non-magnetized objects in Sections 13.6.1 and 13.6.2.

13.1.1 Planetary magnetic fields

Spacecraft carrying magnetometers have flown to and characterized the magnetic fields of all the planets except Pluto. Tables 13.2 and 13.3 list the properties of each planet (the strength and direction of the planet's magnetic field and the rotation rate and direction of the planet's spin), the interplanetary medium (the strength and direction of the interplanetary magnetic field (IMF) and the speed, density, and temperature of the solar wind), as well as the characteristics of the magnetospheres observed to date.

While the theory of planetary dynamos has yet to reach the level of sophistication where it could predict with accuracy the presence (let alone the specific characteristics) of an internally generated magnetic field, it is generally understood that, for such a field to be present, planets need to have an interior that is sufficiently electrically conducting and that is convecting with sufficient vigor (see Chapter 3). The iron cores are potential dynamo regions of terrestrial planets. The high pressures inside the giant planets Jupiter and Saturn put the hydrogen into a phase where it has the electrical conductivity of liquid metal. Inside Uranus and Neptune the pressures are too weak to make hydrogen metallic and it is postulated

Table 13.2. *Properties of the solar wind and scales of planetary magnetospheres*

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Distance a_p (AU)[a]	0.39	0.72	1[b]	1.52	5.2	9.5	19	30	40
Solar wind dens. (cm^{-3})	53	14	7	3	0.2	0.07	0.02	0.006	0.003
IMF strength[c] (nT)	41	14	8	5	1	0.6	0.3	0.2	0.1
IMF azimuth angle[c]	23°	38°	45°	57°	80°	84°	87°	88°	88°
Radius R_p (km)	2439	6051	6373	3394	71 400	60 268	25 600	24 765	1170±33
Sidereal spin period (d)	58.6	−243	0.9973	1.026	0.41	0.44	−0.72	0.67	−6.39
Magnetic moment/M_E[d]	$(3–6) \times 10^{-4}$	$<10^{-5}$	1[d]	$<10^{-5}$	20 000	600	50	25	?
Surface field[e] B_0 (nT)	200–400	—	30 600	—	430 000	21 400	22 800	14 200	?
R_{MP}[f] (R_p)	$1.6R_M$	—	$10R_E$	—	$42R_J$	$19R_S$	$25R_U$	$24R_N$	?
Observed size of magnetosphere	$1.5R_M$	—	$(8–12)R_E$	—	$(50–100)R_J$	$(16–22)R_S$	$18R_U$	$(23–26)R_N$	?

[a] 1 AU = 1.5×10^8 km.

[b] The density of the solar wind fluctuates by about a factor 5 around typical values $\rho_{sw} \sim 7\,(cm^{-3})/a_p^2$.

[c] Mean values. The azimuth angle is $\tan^{-1}(B_\phi/B_r)$. The radial component of the IMF, B_r, decreases as $1/a_p^2$ while the transverse component, B_ϕ, increases with distance (Gosling, 2007).

[d] $M_E = 7.9 \times 10^{25}$ gauss cm^3 $= 7.9 \times 10^{15}$ tesla m^3.

[e] The magnitude of an eccentric dipole: for Earth and the outer planets from Connerney (1993); for Mercury from Connerney and Ness (1988); upper limits for Mars and for Venus (strictly speaking $M_V < 10^{-5} M_E$) from Russell (1993).

[f] R_{MP} is calculated using $R_{MP} = \xi(B_0^2/2\mu_0\rho v_{sw}^2)^{1/6}$ for typical solar wind conditions of ρ_{sw} given above and $v_{sw} \sim 400$ km/s and ξ an empirical factor of ~ 1.4 to match Earth observations (Walker and Russell, 1995).

Table 13.3. *Planetary magnetic fields*

	Ganymede	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
$B_{dip,eq}$ (nT)[a]	719	200–400	30 600	430 000	21 400	22 80	14 200
B_{max}/B_{min}[b]	2	2	2.8	4.5	4.6	12	9
Dipole tilt[c]	$-4°$	$\sim 10°$	$11.2°$	$-9.4°$	$-0.0°$	$-59°$	$-47°$
Dipole offset[d]	—	—	0.076	0.119	0.038	0.352	0.485
Obliquity[e]	$0°$	$0°$	$23.5°$	$3.1°$	$26.7°$	$97.9°$	$29.6°$
$\delta\phi_{sw}$[f]	$90°$	$90°$	$67°$–$114°$	$87°$–$93°$	$64°$–$117°$	$8°$–$172°$	$60°$–$120°$

[a] Surface field at dipole equator. Values derived from modeling the magnetic field as an eccentric dipole (with magnitude, tilt, and offset). Values for Mercury from Connerney and Ness (1988), for Earth and outer planets from Connerney (1993).
[b] Ratio of the maximum surface field to the minimum (equal to 2, for a centered dipole field). This ratio tends to increase with the planet's oblateness.
[c] Angle between the magnetic and rotation axes. Positive values correspond to a magnetic field directed north at the equator. The magnetic poles of the Earth's field are currently located at 83°N and 65°S latitudes and moving about 10° per century (Natural Resources Canada, Australian Antarctic Division).
[d] Values (in planetary radii, R_p) from eccentric dipole models of Connerney (1993).
[e] The inclination of a planet's spin equator to the ecliptic plane.
[f] Range in the angle between the radial direction from the Sun and the planet's rotation axis over an orbital period. In Ganymede's case, the angle is between the corotational flow and the moon's spin axis.

that their dynamos must be generated in regions of liquid water where, as in Earth's ocean, small concentrations of ions provide sufficient conductivity.

Given the disparity in scale between the giant and terrestrial planets (e.g. the volume of Jupiter is 1400 times that of the Earth) it is perhaps not surprising that the four terrestrial planets have far weaker magnetic fields generated in their interiors than the giant planets (Russell, 1993; Connerney, 1993; Stevenson, 2003). Extensive geophysical measurements have revealed substantial information about the distribution of density, temperature, and flows inside the Earth. Moreover, the remanent magnetization of surface rocks tells us how the Earth's field has changed over geological time. These geophysical data are powerful constraints on the geodynamo (Glatzmaier, 2002). For other planetary objects the presence or absence of a magnetic field is an important constraint on their interiors.

The apparent lack of an active dynamo inside Venus puts interesting constraints on the thermal evolution of that planet (Stevenson *et al.*, 1983; Schubert *et al.*, 1988). A common misconception is that it is the slowness of the rotation of Venus that prevents a dynamo. In fact, very little rotation is needed for a dynamo and all objects in the solar system have sufficient rotation (Stevenson, 2003). So, the question becomes "Why is Venus' core not convecting"? One possibility is that Venus' core temperature is too high for a solid iron core to condense (the differentiation of solid iron from an outer liquid sulfur–iron alloy drives Earth's dynamo). The lack of plate tectonics at Venus may be limiting the cooling of the planet's upper layers, further suppressing internal convection. Why planetary neighbors that are almost twins should have suffered such different internal histories is a major mystery of planetary geophysics (Smrekar *et al.*, 2007).

Measurements of its remanent crustal magnetism suggest that Mars has had an active dynamo and experienced changes in polarity over geological time scales (Acuna *et al.*, 2001; Connerney *et al.*, 2004) but stopped generating an internal field some four billion years ago, the dominant explanation being a transition from convection to conduction in cooling the core (Stevenson, 2001).

Having radii of $\sim 40\%$ of the Earth's radius, Mercury and Ganymede were originally expected to have cooled off, shutting down any internal dynamo. But spacecraft fly-bys showed each object to have a significant magnetic field. Thermal models of the particularly large iron core ($>70\%$ of the radius) of Mercury suggest that at least an outer region is likely to be liquid and possibly convecting (Stevenson *et al.*, 1983; Schubert *et al.*, 1988). However, the observed field is much weaker than standard dynamo theory would predict (Stevenson, 2003). Tidal heating in Ganymede's geological past may have kept the giant moon warm, but maintaining a dynamo in the smaller iron core ($\sim 30\%$ of the radius) may have needed enhanced amounts of sulfur, which suppresses the freezing point, and/or additional radiogenic heating (Stevenson, 2003).

13.1.2 Planetary magnetospheres

Figure 1.3 presents a schematic of the Earth's magnetosphere showing the bow shock and magnetopause boundaries as well as the major regions. In Chapter 10 (Eq. 10.1) we derived a characteristic scale for the sub-solar distance of the magnetopause, R_{MP}, by assuming that the pressure of the planet's magnetic field, assumed to be dipolar, balances the ram pressure of the solar wind. Table 13.2 shows that this is a reasonable approximation to the observed magnetospheric scale except in the case of Jupiter, where substantial plasma pressure inside expands the magnetosphere. Figure 13.1 illustrates the huge range in scale of the planetary magnetospheres. The magnetospheres of the giant planets encompass most of their extensive moon systems, including the four Galilean moons of Jupiter as well as Titan and Triton. Earth's Moon, however, resides almost entirely outside the magnetosphere, spending less than 5% of its orbit crossing the magnetotail.

The magnetospheres of Mercury, Earth, and Jupiter form a "small, medium, large" triad (Fig. 2.7): Earth tends to be considered as the standard of comparison for other magnetospheres. It is natural that our home planet's magnetosphere is

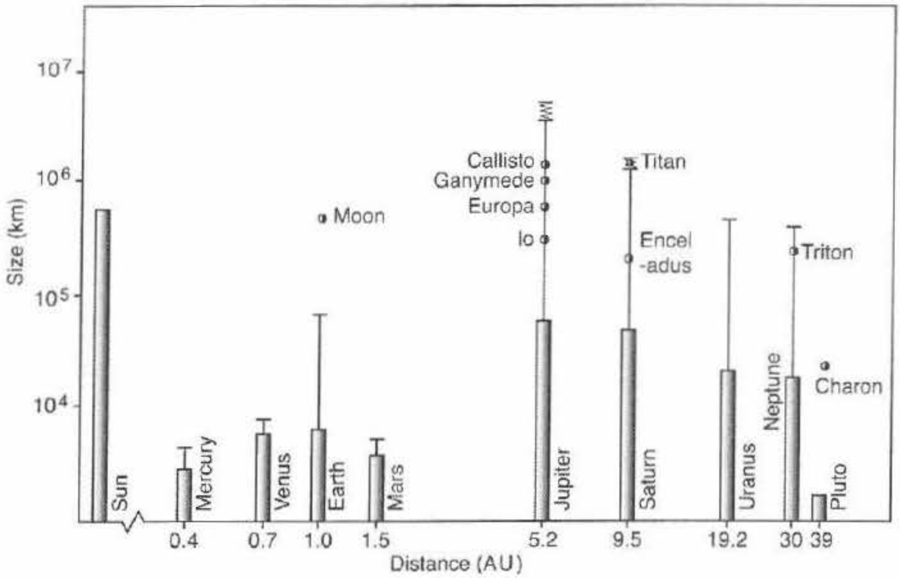

Fig. 13.1. A logarithmic plot of size of object vs. distance from the Sun, for the planets (solid bars), their magnetospheres (thin bars), and the orbital radii of their primary moons. The ranges in size of the magnetospheres of Jupiter and Saturn are shown by the zigzag lines.

better explored and its vicissitudes studied in detail, but it is also important to test our understanding of the magnetospheric principles derived at Earth by applying these concepts to other planets. Figure 2.7 illustrates the vast range in scales: each magnetosphere fits into the volume of the next-larger planet. The expanding solar wind of the heliosphere, as it moves through the interstellar medium, has similarities to a magnetosphere (e.g. it has a heliopause and bow shock). The passage of Voyager 2 through the termination shock at 94 AU gave a scale for the heliosphere that dwarfs the few-AU scale of Jupiter's magnetosphere.

Table 13.3 gives the magnetic moment of each planet and the surface value of the field at the equator on the assumption that each planetary field is dipolar. In reality, when we look closer at a planetary magnetic field we see greater complexity. The standard technique is to describe the internal magnetic field as a sum of multipoles or spherical harmonics (e.g. Walker and Russell, 1995; Connerney, 1993; Merrill *et al.*, 1996), the higher orders being functions that drop off increasingly rapidly with distance so that one needs to get very close to the planet to see any effects of these high-order multipoles. The amplitude of each multipole is derived by fitting magnetic field observations obtained by magnetometers on spacecraft flying past the planet (e.g. Connerney, 1981). The extensive coverage afforded by low-orbiting spacecraft at Earth provides an International Geomagnetic Reference Field with

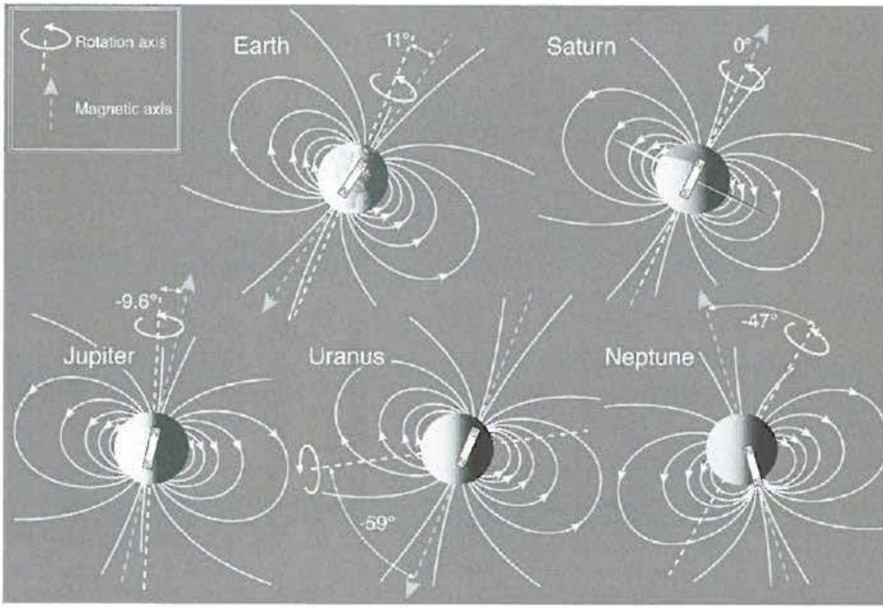

Fig. 13.2. The tilt angles between the spin and magnetic axes are shown for the five main magnetized planets. Considering the horizontal direction of the diagram as parallel to the ecliptic plane and the vertical direction as the ecliptic normal, then the spin axis is shown for conditions of maximum angle from the ecliptic normal (i.e. at solstice). Each planet's magnetic field can be approximated as a dipole, where the orientation and any offset from the center of the planet is illustrated by a bar magnet located at the center of the dipole.

196 harmonic coefficients (IGRF). The level of spacecraft coverage at most other planets limits the description of a planet's magnetic field to little more than a dipole tilted with respect to the spin axis and sometimes offset from the center of the planet. The values in Table 13.3 for the ratio of the minimum and maximum surface magnetic fields, which would have the value 2 for a centered dipole, illustrate the net importance of the non-dipolar components for some planets. At Mercury the observations are too limited to constrain the dipole tilt or offset (Connerney and Ness, 1988). The high values of the maximum/minimum ratios at Uranus and Neptune are symptomatic of highly irregular magnetic fields which can each be crudely characterized as a highly tilted dipole significantly offset from the center of the planet, as illustrated in Figure 13.2. The apparently close alignment of the magnetic field of Saturn with its rotation axis continues to be a puzzle because various of its magnetospheric phenomena exhibit spin modulation (to be discussed further below), which is not expected of an axisymmetric magnetic field.

Finally, when we discuss the dynamics of magnetospheres it will be clear that an important factor is the orientation of the planet's magnetic field relative to the interplanetary magnetic field (Chapter 9). The obliquity is the angle of the planet's spin axis relative to the ecliptic plane normal. As a planet orbits the Sun, if it has a large obliquity it will experience not only large seasonal changes but also a wide range in angles between the upstream solar wind (and embedded IMF) and the planet's magnetic field. Moreover, the large tilt of Uranus' and Neptune's magnetic fields with respect to their spin axes means that these magnetospheres also see a modulation of this solar wind angle over their spin period (i.e. a planetary day). While the solar wind remains flowing within a few degrees of radially from the Sun, the IMF forms a spiral of increasingly tangential field. At Earth the average spiral angle is 45°, at Jupiter it averages 80°, and at farther planets the field is basically tangential to the planet's orbit. The polarity changes several times during the ~25 day solar rotation (more frequently during solar maximum). Most important for magnetospheric dynamics is the variation in the north–south component of the IMF, which fluctuates about the ecliptic plane.

13.1.3 Plasma sources

The plasma found in a planetary magnetosphere could have a variety of sources (see Section 9.5): it could have leaked across the magnetopause from the solar wind, it may have escaped the planet's gravity and flowed out of the ionosphere, or it may be the result of the ionization of neutral material coming from satellites or rings embedded in the magnetosphere. The study of the origin of plasma populations and their evolution as they move through the magnetosphere is a detective story that becomes more complex the deeper one delves (see the review by Moore and Horwitz, 2007).

The clearest indicator of which sources are responsible for a particular planet's magnetospheric plasma is the chemical composition of the latter (Table 13.4). For example, the O^+ ions in the Earth's magnetosphere must surely have come from the ionosphere and the sulfur and oxygen ions at Jupiter have an obvious origin in Io's volcanic gases. But the source of protons is not so clear – protons could be either ionospheric, particularly for the hydrogen-dominated gas giants, or from the solar wind. One might consider that a useful source diagnostic would be the abundance of helium ions. Emanating from the hot (millions of kelvins, a few 100 eV) solar corona, helium in the solar wind is fully ionized as He^{++} ions, and comprises ~ 5% of the number density. Ionospheric plasma is much cooler (thousands of kelvins, < 0.1 eV), so that ionospheric helium ions are mostly singly ionized. Thus, a measurement of the abundance ratios He^{++}/H^+ and He^+/H^+ would clearly distinguish the relative importance of these sources. Unfortunately, measuring the composition to such a level of detail is difficult for the bulk of the plasma, with energies in the range 1 eV to 1 keV (e.g. Young, 1997, 1998). Measurement of

Table 13.4. *Plasma characteristics of planetary magnetospheres*

	Ganymede	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
Max. plasma dens. (cm^{-3})	~ 400	~ 1	~ 4000	~ 3000	~ 100	3	2
Neutral density (cm^{-3})				~ 50	~ 1000		
Major ion species	O^+, H^+	H^+	O^+, H^+	O^{n+}, S^{n+}	O^+, H_2O^+, H^+	H^+	N^+, H^+
Minor ion species		O^+, Na^+ [a]		H^+, H_3^+ [b]			
Dominant source	Ganymede	solar wind	ionosphere[c]	Io	Enceladus	atmosphere	Triton
Neutral source[d] (kg/s)	10			600–2600	2–300		
Plasma source[e] (kg/s)	5	~ 1	5	300–900	10–15 [g]	0.02	0.2
Plasma source[f] (ions/s)	10^{26}	10^{26}	2×10^{26}	$> 10^{28}$	$(3\text{–}5) \times 10^{26}$ [g]	10^{25}	10^{25}
Lifetime[h]	minutes	minutes	hour–days	20–80 days	30–50 days	1–30 days	~ 1 day

[a] Mercury's tenuous atmosphere is a likely source of heavy ions.
[b] An ionospheric source that may be comparable by number to the primary, iogenic source.
[c] Ionospheric plasma dominates the inner magnetosphere; solar wind sources are significant in the outer regions.
[d] Net loss of neutrals from satellite and ring sources (Jupiter: Delamere *et al.*, 2004. Saturn: Hansen *et al.*, 2006; Waite *et al.*, 2006; Tokar *et al.*, 2006; Jurac and Richardson, 2005).
[e] Net production of plasma density (does not include charge exchange processes).
[f] Assumes that 15% of the impinging solar wind flux enters the magnetopause.
[g] Assumes a 5% net ionization rate of neutrals (Delamere *et al.*, 2007).
[h] Typical residence time in the magnetosphere. Plasma stays inside the plasmasphere for days but is convected through the outer magnetosphere in hours.

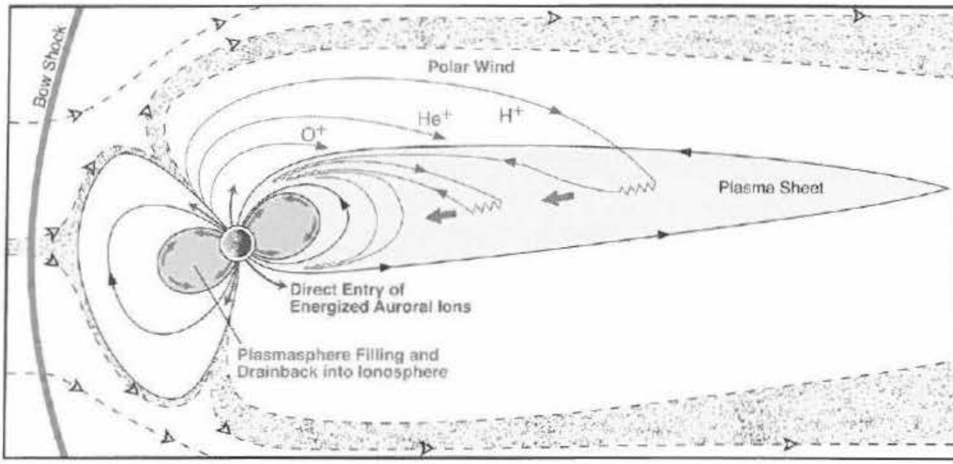

Fig. 13.3. Sources of plasma for the Earth's magnetosphere (after Chappell, 1988). The shaded and dotted area illustrates the boundary layer through which solar wind plasma enters the magnetosphere.

composition is more feasible at higher energies but then one needs to consider whether the process that has accelerated the ions within the magnetosphere since they left the source region is mass or charge dependent.

The temperature of a plasma can also be an indicator of its origin. Plasma in the ionosphere has characteristic temperatures of < 0.1 eV; the ionization of neutral gases produces ions with energies associated with the location flow speed while plasma that has leaked in from the solar wind tends to have energies of a few keV. But, again, we need to consider carefully how a parcel of plasma may have heated or cooled as it moved through the magnetosphere to the location at which it is measured. Figure 13.3 illustrates various ways in which ionospheric plasma enters the Earth's magnetosphere and evolves by different processes. As we explore other magnetospheres we should expect similar levels of complexity.

Table 13.4 summarizes the main plasma characteristics of the six planetary magnetospheres. To a first approximation one can say that sources from removal of material from the satellites dominate the magnetospheres of Jupiter, Saturn, and Neptune, ionospheric sources being secondary. Uranus having fewer, smaller, satellites, its weak ionospheric source probably gives the main contribution. With only the most tenuous of exospheres, Mercury's magnetosphere contains mostly solar wind material, but energetic particle and photon bombardment of the surface may be a significant source of O^+, Na^+, K^+, Mg^+, etc. (Slavin, 2004). At Earth the net sources from the solar wind and ionosphere are probably comparable, though the most recent studies suggest that the ionospheric contribution seems to be dominant (e.g. Moore and Horwitz, 2007).

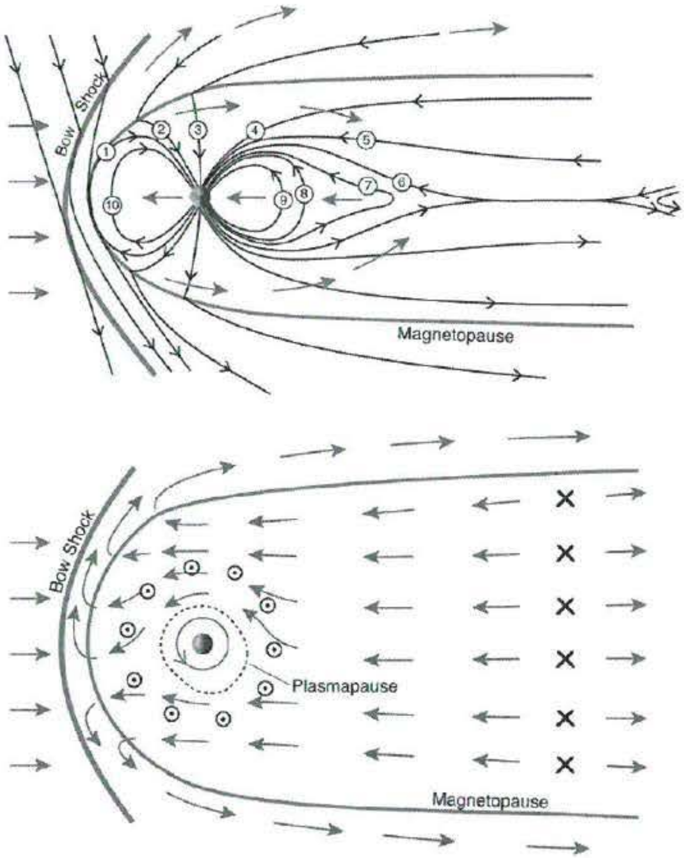

Fig. 13.4. Magnetospheric dynamics associated with the Dungey cycle, which is driven by the solar wind. (Upper panel) The view in the noon–midnight meridian plane. The numbers show the time sequence for a flux tube being reconnected at the dayside magnetopause and convected through the magnetosphere. (Lower panel) The view in the equatorial plane. After Dungey (1961).

13.1.4 Plasma dynamics

In Chapter 10 we developed a general theory of how magnetospheric plasma motions are driven by coupling either to the solar wind or to the rotation of the planet. Figure 13.4 shows how reconnection of the planet's magnetic field with the interplanetary field (often involving flux-transfer events; see Section 6.5.4) harnesses the momentum of the solar wind and drives the circulation of plasma within the magnetosphere; this circulation is sometimes called the Dungey cycle (Dungey, 1961). Figure 13.5 illustrates the main alternative dynamical process whereby the magnetospheric plasma is coupled to the angular momentum of the spinning planet. We will now apply these ideas to the specific planetary magnetospheres. Table 13.6

Table 13.5. *Energetic-particle characteristics in planetary magnetospheres*

	Earth	Jupiter	Saturn	Uranus	Neptune
Phase space density[a]	20 000	200 000	60 000	800	800
Plasma β[b]	< 1	> 1	> 1	~ 0.1	~ 0.2
Ring current[c] ΔB (nT)	10–23	200	10	< 1	< 0.1
Auroral power (watts)	10^{10}	10^{14}	10^{11}	10^{11}	$< 10^{8}$

[a] The phase space density of energetic particles (in this case 100 MeV/gauss ions) is measured in units of c^2 (cm^2 sr MeV^3)$^{-1}$ and is listed near its maximum value.
[b] The ratio of the thermal energy density and the magnetic energy density of a plasma, $\beta = nkT/(\mu_0^{-1} B^2)$. These values are typical for the body of the magnetosphere. Higher values are often found in the tail plasma sheet and, in the case of the Earth, at times of enhanced ring current.
[c] The magnetic field produced at the surface of the planet due to the ring current of energetic particles in the planet's magnetosphere.

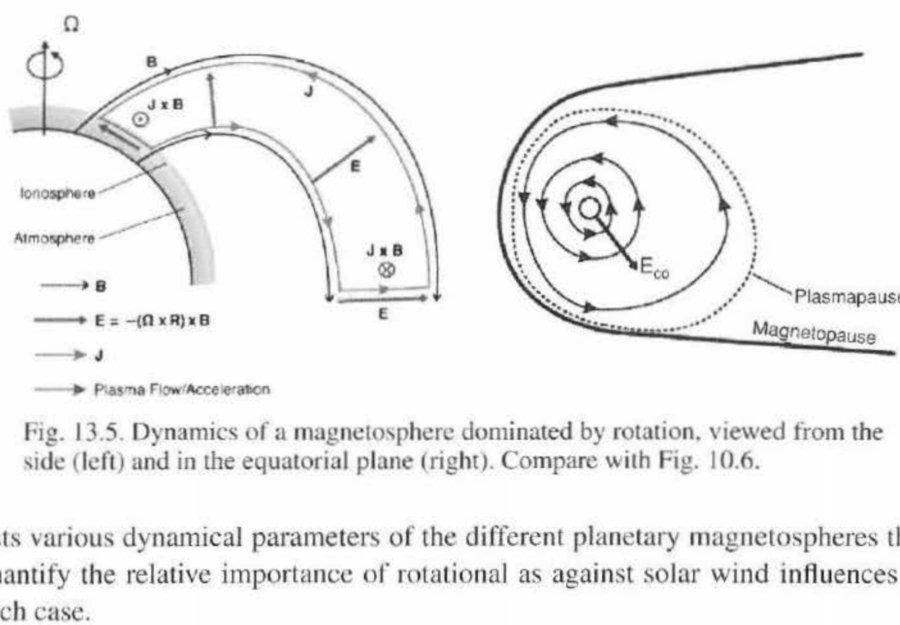

Fig. 13.5. Dynamics of a magnetosphere dominated by rotation, viewed from the side (left) and in the equatorial plane (right). Compare with Fig. 10.6.

lists various dynamical parameters of the different planetary magnetospheres that quantify the relative importance of rotational as against solar wind influences in each case.

First, let us quantify the spatial and temporal scales over which the Dungey cycle would operate at each planet. Let us further suppose that for some fraction of the time there is a component of the IMF that is opposite to the direction of the planetary magnetic field at the magnetopause (e.g. a negative B_z for Earth and a positive B_z for Jupiter and Saturn; we ignore the complexities of Uranus and Neptune for the moment). Such a configuration allows the reconnection of planetary and interplanetary fields at the dayside magnetopause (see step 1 of Figure 13.4). Now we have one end of the flux tube attached to the planet and the

Table 13.6. *Estimated dynamical characteristics of planetary magnetospheres*

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
R_{MP}[a] (km)	4000	6.5×10^4	6×10^6	1×10^6	6×10^5	6×10^5
v_{sw} speed[b]	370	390	420	430	450	460
t_{N-T}[c]	10 s	3 min	4 hr	45 min	20 min	20 min
R_T[d] (R_p)	3	20	170	40	50	50
R_T[e] (km)	8000	1.3×10^5	1.2×10^7	2.3×10^6	1.3×10^6	1.2×10^6
$v_{rec,1}$[e]	40	22	16	16	16	16
$v_{rec,2}$[f]	37	39	42	43	45	46
t_{rec}[g]	3 min	1 hr	80 hr	15 hr	8 hr	7 hr
d_X[h] (R_p)	30	200	1700	400	500	500
$v_{co}/v_{rec,2}$[i]	4×10^{-5}	0.04	8	1.3	0.4	0.4
d_{pp}[j] (R_p)	0.03	6.7	350	95	70	70

[a] Sub-solar magnetopause radius (see Section 9.1).
[b] $v_{sw} = 387(a_p/a_E)^{0.05}$ km/s, from Belcher *et al.* (1993).
[c] Solar wind nose–terminator time: $t_{N-T} \equiv R_{MP}/v_{sw}$.
[d] Radius of cross section of magnetotail, approximated as $R_T = 2R_{MP}$.
[e] Reconnection speed assuming 20% reconnection efficiency and that $v_{rec,1} \sim 0.2 v_{sw} B_{sw}/B_{MP}$ km/s (e.g. Kivelson, 2007);
[f] Reconnection speed assuming 10% reconnection efficiency and $v_{rec,2} \sim 0.1 v_{sw}$ km/s.
[g] Reconnection time $t_{rec} = R_T/v_{rec,2}$ s.
[h] Distance to X-line $d_X = v_{sw} t_{rec}$.
[i] Assumes that the rotation speed at the magnetopause is $\sim 30\%$ that for rigid corotation.
[j] Distance to the plasmapause, where the corotation is comparable to the reconnection flow (e.g. Kivelson 2007).

other is out in the solar wind. To estimate how long it takes the section of flux tube in the solar wind to move to the plane of the planet's terminator (step 3), we divide the sub-solar magnetopause distance R_{MP} by the local solar wind speed. For Table 13.6 we used an empirical fit to Voyager data that includes a modest increase in the solar wind speed with distance from the Sun, but the basic results would not be very different if a constant value for the solar wind (say ~ 400 km/s) were used. One immediately sees the effect of the vast scale of the giant magnetospheres of the outer planets: the nose-terminator time scale is a mere 10 seconds at Mercury, 3 minutes at Earth, and as much as 4 hours at Jupiter.

The next step is to calculate how long the open flux tube would take to convect to the equator or central plane of the magnetotail (from step 3 to step 6 in Figure 13.4). For simplicity, the radius of each magnetotail has been approximated as twice the sub-solar standoff distance (i.e. $2R_{MP}$). This probably underestimates the cross-sectional radius of real magnetotails. We need to divide this distance by a convective speed to estimate a minimum convective time scale. The traditional approach to calculating the speed of circulation in the magnetosphere driven by solar wind, coupling was to calculate the electric field associated with an object moving with the planet relative to the solar wind, $\mathbf{E}_{sw} = -\mathbf{v}_{sw} \times \mathbf{B}_{IMF}$, assume that some fraction (say, 20%) of this electric field permeates the whole magnetosphere (i.e. the convective electric field $\mathbf{E}_{con} \approx 0.2\mathbf{E}_{sw}$), and then estimate how magnetospheric plasma would drift in this convection electric field and the local planetary magnetic field ($\mathbf{v}_{con} = \mathbf{E}_{con} \times \mathbf{B}_{planet}$) (e.g. Cravens, 1997; Bagenal, 1992). However, this approach begs the question of how the electric field permeates the magnetosphere and in which reference frame one should calculate the electric field. An alternative approach that avoids such a conundrum was presented in Chapter 10 (elaborated further in Southwood and Kivelson, 2007). Here, to obtain a rough upper estimate for a reconnection-driven convection speed we have just taken 10% of the solar wind speed (roughly 40 km/s at all planets). Again, the large scales of the giant planet magnetospheres mean that even with generous values for the convection speed one obtains long time scales for flux tubes to convect to the equator from the upper and lower magnetopause boundaries. At Jupiter this time scale is 80 hours, equivalent to eight full rotation periods. The time scales for steps 3–6 of the Dungey cycle for the other giant planets are much less, but they are still several hours and comparable with the planetary rotation rate. By contrast, this convection time scale is just an hour at Earth and a few minutes at Mercury.

The Dungey-cycle time scale mentioned above can also be used to estimate the length of the magnetotail, by multiplying the reconnection time scale and the solar wind speed. More accurately, it gives us the distance down the tail to the X-line, where further reconnection closes the open magnetic flux (hence conserving, on average, the total magnetic flux emanating from the planet). The re-closed magnetic flux tube then convects sunward (steps 7–10 in Figure 13.4) to begin the Dungey cycle again at the dayside magnetopause. Table 13.6 shows that values for this X-line (often called, for obscure reasons, the distant Earth neutral line). This X-line distance is about $20R_{MP}$ if one takes the reconnection-driven convective speed v_{con} to be 10% of v_{sw} and the tail radius to be $2R_{MP}$. Lower estimates of v_{con} give larger distances to the tail X-line. In practice, we know that the Earth's tail extends for several thousand R_E while Jupiter's magnetotail was encountered by Voyager 2 as it approached Saturn at a distance greater than $9000R_J$ or 4 AU downstream of Jupiter. The estimates of distances to magnetotail X-lines derived from simple Dungey cycle principles shown in Table 13.6 illustrate the vast scales of the magnetospheres of the outer planets and the huge distances that flux tubes reconnecting (re-closing) in the tail would need to travel back to the planet if these magnetospheres were driven by Earth-like processes.

Next we need to compare the relative importance of the reconnection-driving Dungey cycle and the effects of the planet's rotating magnetic field. Again, the traditional approach has been to consider electric fields and to compare the convection electric field $\mathbf{E}_{sw}$ with the corotational electric field, $\mathbf{E}_{cor} = -(\mathbf{\Omega} \times \mathbf{R}) \times \mathbf{B}_{planet}$ (e.g. Cravens, 1997; Bagenal, 1992). In Chapter 10 we compared the electric potentials across the polar cap associated with the two types of flow (Eq. 10.18). We compared the corotation speed $v_{cor} = |\mathbf{\Omega} \times \mathbf{R}|$ with our upper estimate of the convection flows driven by reconnection, v_{con}. The very low values in Table 13.6 of v_{cor}/v_{con} for Mercury and Earth confirm that the dynamics of these magnetospheres are dominated by coupling to the solar wind while it is clearly the case that rotation dominates Jupiter and Saturn. Uranus and Neptune, once again, are not simple cases with speed ratios of order unity that would suggest the comparable importance of rotation and solar-wind-driven circulation.

In a general sense, close to the planet where the magnetic field is strong and rotation speeds are low one expects strong coupling to the planet's rotation. At larger distances from the planet, one expects decreasing corotation and an increasing influence of the solar wind. Finally, we can estimate the size R_{pp} of a region (called the plasmapause at Earth) within which rotation flows dominate solar-wind-driven flows. The values for R_{pp} in the bottom row of Table 13.6 further illustrate how the planets' magnetospheres span the range between the extremes of Jupiter (where $R_{pp} \gg 1$ and rotation dominates throughout) and Mercury (where $R_{PP} \ll 1$ means that there is no region of corotating plasma in the tiny magnetosphere).

13.1.5 Energetic particles

At all magnetospheres there are substantial populations of particles with energies far greater than at their original sources. In Table 13.5 some of the properties of non-thermal particles in different magnetospheres are given for comparison. Figure 13.3 shows some of the processes whereby ions and electrons in the ionospheric plasma at Earth are accelerated; in the Earth's auroral regions this occurs by intense local electric and magnetic fields. In the polar regions heated ionospheric oxygen, helium, and hydrogen ions escape the planet as a polar wind that flows away from the planet on the nightside. The lighter ions extend farther down the tail before drifting towards the plasma sheet that sits at the nightside magnetic equator. In the plasma sheet ions are scattered and accelerated by the local electric and magnetic fields. Plasma in the plasma sheet is also accelerated as it convects from the tail towards the planet in the second half of the Dungey cycle (Fig. 13.4). As particles reach energies of tens of keV they experience significant drifts due to magnetic field gradients (e.g. Cravens, 1997). The ions and electrons drift in opposite directions, producing a ring of electrical current that circles the planet. Further energy is transferred to the convecting energetic particles by low-frequency oscillations of the Earth's magnetic field, producing the radiation-belt particles at $\sim$ tens of MeV energies. The sources and losses of these energetic particles depend strongly on geomagnetic activity.

In the rotation-dominated magnetospheres of Jupiter and Saturn the plasma is accelerated as it moves outward. The details of the acceleration mechanism(s) are far from understood but it is likely that the source of energy is the rotation of the planet, coupled by to the plasma by its strong magnetic field. The interaction of magnetospheric ions with neutral atoms and molecules in the extended satellite atmospheres involves charge-exchange reactions whereby a corotating ion becomes neutralized. The momentum of the neutralized particle is well above the planet's escape speed, so the particles flee the system as energetic neutral atoms. These escaping neutral atoms have been imaged as Jupiter's giant neutral-sodium cloud (Mendillo *et al.*, 1990; Thomas *et al.*, 2004) and detected in situ at both Jupiter and Saturn. A small fraction of these escaping neutrals become re-ionized by solar photons in the outer magnetosphere or neighboring solar wind. The large rotational energies farther out mean that these new ions pick up substantial gyro-energy (perhaps MeV) on ionization. As these fresh energetic ions move inwards into stronger magnetic fields they gain further energy through conservation of the first adiabatic invariant. Such processes are the source of the high fluxes of energetic particles in the inner magnetosphere that bombard the moons and make exploration with spacecraft that carry sensitive electronics so challenging. Most of the inward-moving energetic particles are absorbed by satellites or their neutral clouds. Some particles, however, make their way (over time scales of years) to the inner radiation belts at Jupiter which produce intense synchrotron emission at decimetric wavelengths (see the review by Bolton *et al.*, 2004). The smaller physical scale and shorter time scales of the Saturn system result in less net acceleration and weaker fluxes of energetic particles. Absorption by the majestic ring system further prevents the build-up of comparable fluxes close to the planet, so that there are no synchrotron-emitting belts at Saturn. Significant populations of energetic particles were detected at Uranus and Neptune but the fluxes were much lower than at Jupiter and Saturn. It could be that the shorter residence times in these smaller magnetospheres limit the amount of acceleration or it may be much harder for particles to be stably trapped in such non-dipolar fields.

13.2 Jupiter

Jupiter is a planet of superlatives: the most massive planet in the solar system, which rotates the fastest, has the strongest magnetic field, and has the most massive satellite system of any planet. These unique properties lead to volcanos on Io and a population of energetic plasma trapped in the magnetic field that provides a physical link between the satellites, particularly Io, and the planet Jupiter. For those seeking further details, the jovian magnetosphere is reviewed in seven chapters of *Jupiter: The Planet, Satellites and Magnetosphere* covering topics of plasma interactions with the satellites (Bagenal *et al.*, 2004).

Clear indications that Jupiter traps electrons in its magnetic field were apparent as soon as astronomers turned radio receivers to the sky. Early radio measurements showed that Jupiter has a strong magnetic field tilted about 10° from the spin axis, that energetic (MeV) electrons were trapped at the equator close to the planet, and that Io must be interacting with the surrounding plasma and triggering bursts of emission. The magnetometers and particle detectors on Pioneer 10 (1973) and Pioneer 11 (1974) revealed the vastness of Jupiter's magnetosphere and made in situ measurements on energetic ions and electrons. The Voyager 1 fly-by in 1979 revealed Io's prodigious volcanic activity, thus explaining why this innermost Galilean moon plays such a strong role. Additional data came from subsequent traversals by the Ulysses (1992) and Cassini (2000) spacecraft, but it was the 34 orbits of Galileo (1995–2003) around Jupiter that mapped out magnetospheric structures and monitored their temporal variability. As at Earth, magnetospheric activity is projected onto the planet's atmosphere via auroral emissions; this has been observed from X-rays to radio wavelengths with ground- and space-based telescopes. Jupiter has the advantage for us over the rest of the outer planets of not just being very large but also being much closer, allowing high-quality measurements to be made from Earth.

The magnetosphere of Jupiter extends well beyond the orbits of the Galilean satellite system (Fig. 13.1), and it is these moons that provide much of the plasma (Table 13.4) and some interesting magnetospheric phenomena. In particular, Io loses about 1 tonne per second of atmospheric material (mostly SO_2 and dissociation products), which, when ionized to sulfur and oxygen ions, becomes trapped in Jupiter's magnetic field. Coupling to Jupiter causes the magnetospheric plasma to corotate with the planet. Strong centrifugal forces confine the plasma towards the equator. Thus, the densest plasma forms a torus around Jupiter at the orbit of Io (see the review by Thomas *et al.*, 2004).

Compared with the local plasma, which is corotating with Jupiter at 74 km/s, the neutral atoms are moving slowly, close to Io's orbital speed of 17 km/s. When a neutral atom becomes ionized (via electron impact) it experiences an electric field, resulting in a gyromotion of 57 km/s. Thus, new S^+ and O^+ ions gain 540 eV and 270 eV in gyro-energy. The new "pick-up" ion is also accelerated up to the speed of the surrounding plasma. The necessary momentum comes from the torus plasma, which is in turn coupled, via field-aligned currents, to Jupiter – the jovian flywheel being the ultimate source of momentum and energy for most processes in the magnetosphere. About one-third to one-half of the neutral atoms are ionized to produce additional fresh plasma while the rest are lost via reactions in which a neutral atom exchanges an electron with a torus ion. On becoming neutralized the particle is no longer confined by the magnetic field and flies off as an energetic neutral atom. This charge-exchange process adds gyro-energy to the ions and extracts momentum from the surrounding plasma, but it does not add more plasma to the system.

The Io plasma torus has total mass ~ 2 megatonnes, which would be replenished by a source of ~ 1 tonne/s in ~ 23 days. Multiplying by a typical energy ($T_i \approx$ 60 eV, $T_e \approx 5$ eV) we obtain $\sim 6 \times 10^{17}$ J for the total thermal energy of the torus. The observed UV power is about 1.5 TW, emitted via more than 50 ion spectral lines, most of which are in the EUV. This emission would drain all the energy of the torus electrons in ~ 7 hours. Ion pickup replenishes energy, and Coulomb collisions feed the energy from ions to electrons, but not at a sufficient rate to maintain the observed emissions. A source of additional energy, perhaps mediated via plasma waves, seems to be supplying hot electrons and a comparable amount of energy as ion pickup.

Voyager, Galileo, and, particularly, Cassini observations of UV emissions from the torus show temporal variability (by about a factor 2) in torus properties (Steffl *et al.*, 2004, 2006). Models of the physical chemistry of the torus match the observed properties in regard to the production of neutral O and S atoms, a radial transport time, and a source of hot electrons (Delamere and Bagenal, 2003). Furthermore, the variation in torus emissions observed over several months by Cassini reflect the observed changes in the output of Io's volcanic plumes (Delamere *et al.*, 2004).

13.2.1 Plasma transport

The earliest theoretical studies concluded that the magnetosphere of Jupiter is "all plasmasphere" with little influence of solar-wind-driven convection (Brice and Ioannidis, 1970). Indeed, rotation dominates the plasma flows observed in the jovian magnetosphere out to distances $\sim 70 R_J$ (Frank *et al.*, 2002; Krupp *et al.*, 2001, 2004). Yet, the presence of sulfur and oxygen ions in the middle magnetosphere, far from Io, indicates that plasma is transported outwards, in directions transverse to the magnetic field.

Rotation-dominated magnetospheres can be thought of as a giant centrifuge with outward radial transport being strongly favored over inward transport. Radial transport of the Iogenic plasma is thought to occur through a process of flux-tube interchange, a diffusive process analogous to the Rayleigh–Taylor instability of fluid dynamics. Flux tubes laden with denser, cooler, plasma move outwards and relatively empty flux tubes containing hotter plasma from the outer magnetosphere move inwards. The 20–80 day time scale (equivalent to 50–200 rotations) for the replacement of the torus indicates surprisingly slow radial transport that maintains a relatively strong radial density gradient. Numerical modeling suggests that radial shear in the azimuthal flow (i.e. increasing lag behind corotation with increasing distance) stabilizes the interchange motion and drives the characteristic size of interchanging flux tubes to small scales (Pontius *et al.*, 1998; Wu *et al.*, 2007).

The net radial transport is thought to be slowest near Io's orbit (~ 15 m/s) and to speed up farther out (~ 50 m/s beyond $10R_J$). Plasma from the Io torus spreads out from Jupiter as a $\sim 5R_J$-thick plasma sheet throughout the magnetosphere. While the flow direction remains primarily rotational, both a lag behind corotation and local time asymmetries increase steadily with distance from the planet. Bursts of flow down the magnetotail are observed and also, on the dawn flanks, occasional strong bursts of super-rotation (Krupp *et al.*, 2004). Below we return to these deviations from co-rotation and discuss how they relate to auroral structures.

13.2.2 Field structure

As the equatorial plasma rotates rapidly it exerts a radial (centrifugal) stress on the flux tubes. Additional stress is provided by the radial pressure gradient of the plasma, inflating the magnetic field (see Fig. 13.6). The net result is a stretching of the initially dipolar field lines away from the planet, in a configuration that implies an azimuthal current in the near-equatorial disk (Fig. 13.6(a)). The lower two panels of Figure 13.6 show magnetic field lines derived from models that include the internally generated field plus the effects of currents on the magnetopause and in the plasma sheet. Figure 13.6(d) shows magnetic field lines projected onto the equatorial plane and illustrates how the field lines also bend or "curl" in the azimuthal direction, which means that there are also radial currents in the equatorial plasma sheet (Fig. 13.6(b)). Alternatively one can think of sub-corotating plasma pulling the magnetic field away from radial. At Jupiter, the field is more or less azimuthally symmetric out to about $50R_J$ but Fig. 13.6(d) shows that strong local time asymmetries develop in the outer magnetosphere (Khurana, 2001, 2005).

An important consequence of a strong internal plasma source and an equatorial plasma sheet is that the magnetosphere becomes more compressible. A simple pressure balance between the ram pressure of the solar wind and the magnetic pressure of a dipole produces a weak variation in the terrestrial dayside magnetopause distance R_{MP} for a solar wind density ρ and speed v_{sw} such that $R_{MP} \propto (\rho v_{sw}^2)^{-1/6}$. Measurements of the magnetopause locations at Jupiter indicate a much stronger variation, $R_{MP} \propto (\rho v_{sw}^2)^{-1/3}$. Consequently, a factor 10 variation in ram pressure at Earth changes the magnetopause distance by only 70% while at Jupiter the tenfold variations in solar wind pressure often observed at 5 AU cause the dayside magnetopause to move between $\sim 100R_J$ and $\sim 50R_J$. This greater compressibility of the jovian magnetosphere is due to a significant contribution of the plasma pressure in

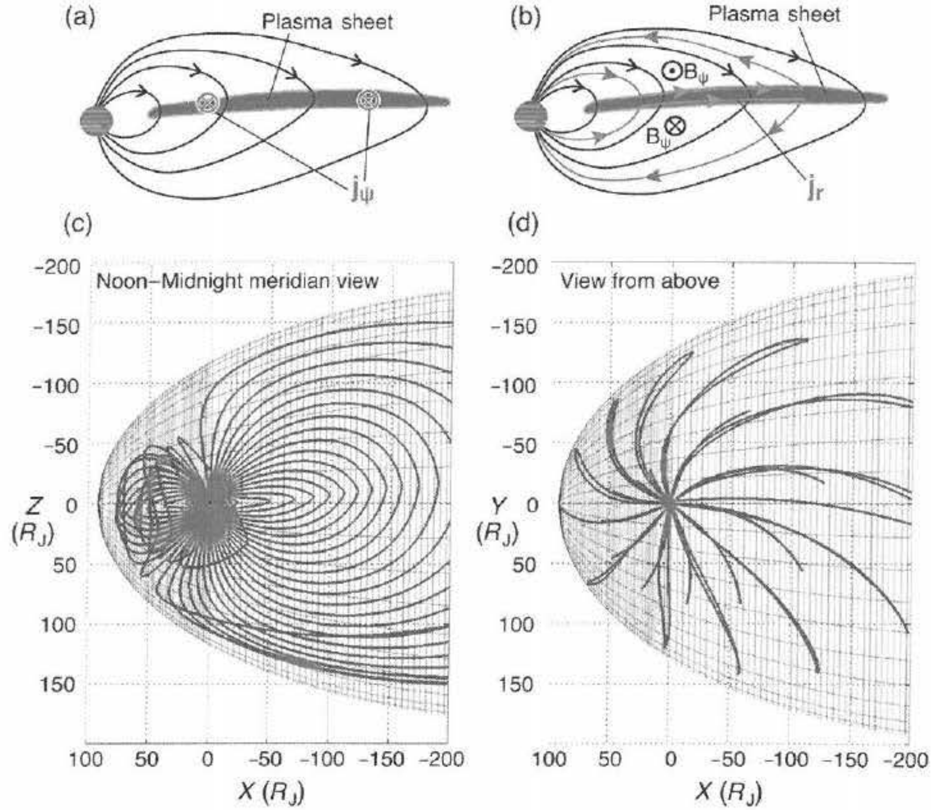

Fig. 13.6. Magnetic field configuration and current systems in Jupiter's magnetosphere. The upper panels show the (a) azimuthal and (b) radial current systems. The lower panels show the magnetic field configuration (c) in the noon–midnight meridian plane and (d) in the equatorial plane; they were derived from in situ magnetic field measurements (Khurana and Schwarzl, 2005). Compare with the schematic representation in Fig. 10.6 discussed in Section 10.4.4.

the equatorial plasma sheet as well as a substantial system of azimuthal currents that weaken the radial gradient of the magnetic field compared to that of a dipole (illustrated in Fig. 10.2).

13.2.3 Aurora at Jupiter

Just as at Earth, the auroral emissions at Jupiter are important indicators of magnetospheric processes. With limited spacecraft coverage of these magnetospheres, auroral activity is a projection of magnetospheric processes, communicated via precipitating energetic particles, onto the atmosphere; thus it allows us to study global processes not yet accessed by spacecraft. Figure 13.7 illustrates the three main types of aurora at Jupiter (see the reviews by Bhardwaj and Gladstone, 2000,

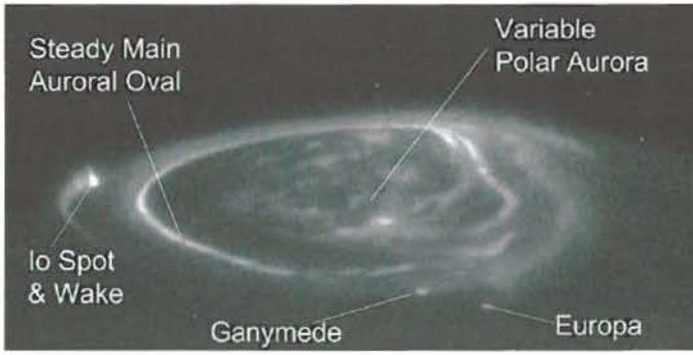

Fig. 13.7. The three main types of auroral emissions at Jupiter: the main aurora, satellite footprint emissions, and polar aurora (Clarke *et al.*, 2004).

and Clarke *et al.*, 2004). There is a fairly steady main auroral oval that produces approximately 10^{14} W globally and that can exceed $1\,\mathrm{W\,m^{-2}}$ locally. This oval is quite narrow, corresponding to about one degree in latitude or a few hundred kilometers horizontally in the atmosphere of Jupiter and mapping along magnetic field lines to $(20–30)R_J$ at the equator in the magnetosphere, well inside the magnetopause. Auroral emissions are also observed at the feet of flux tubes at Io, Europa, and Ganymede. While the magnetosphere interaction with Callisto is thought to be much weaker than for the other satellites, any Callisto aurora would be difficult to separate from the main aurora. The Io-related aurora includes a "wake" signature that extends half-way around Jupiter. The third type of jovian aurora is the highly variable polar aurora, which occurs at higher latitudes than the main aurora, corresponding to greater magnetospheric distances.

The fact that the shape of the jovian main auroral oval is constant and fixed, in magnetic coordinates (including an indication of a persistent magnetic anomaly in the northern hemisphere), tells us that the auroral emissions correspond to a persistent magnetospheric process that causes a more or less constant bombardment of electrons onto Jupiter's atmosphere. Unlike the terrestrial auroral oval, the jovian oval has no relation to the boundary between open and closed field lines of the polar cap; it maps to regions well within the magnetosphere. It is difficult to map the magnetic field lines accurately because of the strong equatorial currents, which are variable and imprecisely determined. But it has become clear that the main aurora is the signature of Jupiter's attempt to spin up its magnetosphere or, more accurately, Jupiter's failure to spin up its magnetosphere fully.

Figure 13.6(b) shows the simple current system proposed by Hill (1979). As the Iogenic plasma moves outwards, the conservation of angular momentum would suggest that the plasma should lose angular speed. In a magnetized plasma, however, electrical currents easily flow along magnetic fields and couple the magnetospheric plasma to Jupiter's flywheel. Hill (1979) argued that at some point the load on the ionosphere increases to the point where the coupling between the ionosphere and corotating atmosphere – manifested as the ionospheric conductivity – is not sufficient to carry the necessary current, causing the plasma to lag behind corotation. Using a simple dipole magnetic field, Hill (1979) obtained an expression for the critical distance for corotation lag that depended on the mass production and transport from Io and the (poorly determined) ionospheric conductivity. Matching his simple model to the Voyager observations of McNutt *et al.* (1979), Hill (1980) found he could model the observed profiles of azimuthal flow with a source giving 2–5 tonne/s and an ionospheric conductivity equal to 0.1 mho. Over the past five years Jupiter's main aurora has become an active area of study. Researchers have considered the effects of the non-dipolar nature of the magnetic field, the narrowness of the auroral emissions, realistic mass-loading rates, the non-linear feedback of ionospheric conductivity responding to electron precipitation, and the development of electrostatic potential drops in the region of low density between the ionosphere and torus (Cowley *et al.*, 2002, 2003a,b; Nichols and Cowley, 2004, 2005). The understanding of plasma processes developed in the terrestrial magnetosphere is being applied to the different regimes at Jupiter and will ultimately be tested when the Juno spacecraft goes into a close polar orbit (planned for 2016).

The auroral emissions poleward of the main auroral oval (see Fig. 13.7) are highly variable; they are modulated by the solar wind and controlled in local time, being usually dark on the dawn side and brighter on the dusk side (see the reviews by Grodent *et al.*, 2003a; Clarke *et al.*, 2004). The region of magnetic field lines that is open to the solar wind in the polar cap is thought to be very small ($< 10^\circ$). Thus, most polar auroral activity reflects activity in the outer magnetosphere, occurring on closed magnetic field lines. Polar auroral activity has been associated with polar cusps (Pallier and Prange, 2004; Bunce *et al.*, 2004), as well as tail plasma sheet reconnection and the ejection of plasmoids down the magnetotail (Grodent *et al.*, 2003b). Spectral observations of auroral X-ray flares suggest that energetic ions are bombarding the polar atmosphere and may be the signature of the plasma sheet return (downward) current (Waite *et al.*, 1994) or accelerated solar wind ions (Gladstone *et al.*, 2002).

13.2.4 Outer magnetosphere dynamics

A major interest in studying the aurora is to explore how the various emissions are related to the dynamics of the outer magnetosphere; see Kivelson and Southwood (2005) and the reviews by Khurana *et al.* (2004); and Krupp *et al.* (2004). The innermost region, which we will call the Hill region, comprises the equatorial plasma disk where rotation dominates the flow. At a distance of about $20 R_J$ the lag of plasma in the equatorial plasma sheet behind strict corotation drives upward currents, and the associated electron bombardment of the atmosphere causes the main aurora.

The middle magnetosphere is a compressible region (sometimes called the "cushion" or Vasyliūnas region, after his seminal article (Vasyliūnas, 1983) in which the dynamics of the outer magnetosphere was first addressed in a substantial fashion). On the dayside of the magnetosphere the ram pressure of the solar wind compresses the magnetosphere. Inward motion on the dawn side reduces the load on the ionosphere, producing a correspondingly dark region in the dawn polar aurora (Fig. 13.7). On the dusk side the plasma expands outwards and strong currents try to keep the magnetospheric plasma corotating. These strong currents produce the active dusk polar aurora. Kivelson and Southwood (2005) argued that the rapid expansion of flux tubes in the afternoon to dusk sector means that the second adiabatic invariant is not conserved, which results in the heating and thickening of the plasma sheet. As the plasma rotates around onto the nightside it is no longer confined by magnetopause currents, moves farther from the planet, and stretches the magnetic field with it. At some point either the coupling to the planet breaks down completely (e.g. because the Alfvén travel time between the equator and the poles becomes a substantial fraction of a rotational period) or the field becomes so radially extended that an X-point develops and a blob of plasma detaches and escapes down the magnetotail, as suggested by Vasyliūnas (1983). Kivelson and Southwood (2005) pointed out that the stretched equatorial magnetic field becomes so weak that the gyroradii of the heavy ions become comparable to the scales of local gradients. It is possible that the plasma diffuses across the magnetic field and "drizzles" down the magnetotail. If the process were entirely diffusive then the magnetic flux would remain connected to Jupiter. The flux tubes would become unloaded and presumably dipolarize as they swung around to the dayside. This is in contrast with the concept of a "planetary wind" (Brice and Ioannidis, 1970; Hill *et al.*, 1974) where a super-Alfvénic plasma wind (in pre-Voyager days assumed to come from the planet) blows the magnetic field open and carries flux down the tail (analogously to the solar wind). As the Voyager spacecraft exited the dawn magnetosphere at distances of about $150R_J$, strong tailward bursts of kiloelectronvolt Iogenic heavy ions were detected, which Krimigis *et al.* (1981) called a magnetospheric wind.

The volume of the magnetosphere that is open to the solar wind is completely unknown. Cowley *et al.* (2003a) postulated that there is a Dungey cycle (similar to that of Earth), driven by dayside reconnection, that carries flux over the poles. Cowley *et al.* argued that the return flow (after tail reconnection) proceeds around to dayside, flanking the dawn magnetopause. There is no evidence as yet of such a solar-wind-induced convection pattern, nor do we know how much polar flux is open to the solar wind. Furthermore, that the time scale for open flux tubes to complete a full Dungey cycle is hundreds of hours or tens of rotation periods raises the issue of the topology of the flux tubes that remain connected to the planet at one end while the other is carried down the tail and towards the equator.

13.2.5 Jovian magnetotail

Pursuing evidence for Vasyliūnas' argument that plasmoids are ejected down the jovian magnetotail, Grodent *et al.* (2003b) found evidence of spots of auroral emission poleward of the main aurora connected to the nightside magnetosphere that flashed with an approximately 10 minute duration. Such events were rare, recurring only about once per 1–2 days. These flashes seemed to occur in the pre-midnight sector, and Grodent *et al.* (2003b) estimated that they are coupled to a region of the magnetotail that was about $5R_J$ to $50R_J$ across and located further than $100R_J$ down the tail. Studies of in situ measurements by Russell *et al.* (2000) and Woch *et al.* (2002) led to the conclusion that plasmoids on the order of $\sim 25R_J$ in scale were being ejected every 4 hours to 3 days, with a predominance for the post-midnight sector and distances of $70R_J$–$120R_J$. Could such plasmoids account for most of the plasma loss down the magnetotail? Bagenal (2007) approximated a plasmoid as a disk of plasma sheet $2R_J$ thick having diameter $25R_J$ and density of $0.01\ \mathrm{cm}^{-3}$, so that each plasmoid has a mass of about 500 tonnes. Ejecting one such plasmoid per day is equivalent to losing 0.006 tonne/s. Increasing the frequency to once per hour raises the loss rate to 0.15 tonne/s. Thus, on the one hand even with optimistic numbers the loss of plasma from the magnetosphere due to such plasmoid ejections cannot match the canonical plasma production rate, 0.5 tonne/s. On the other hand, a steady flow of plasma of density $0.01\ \mathrm{cm}^{-3}$, in a conduit that is $5R_J$ thick and $100R_J$ wide, moving at a speed of 200 km/s would provide a loss of 0.5 tonne/s. Such numbers suggest that a quasi-steady loss rate is feasible. The question of the mechanism remains unanswered. Bagenal (2007) proposed three options: a diffusive "drizzle" across weak, highly stretched, magnetotail fields, a quasi-steady reconnection of small plasmoids, below the scale detectable via auroral emissions, or a continuous but perhaps gusty magnetospheric wind.

In the spring of 2007 the New Horizons spacecraft flew past Jupiter, getting a gravitational boost on its way to Pluto, and made an unprecedented passage down the core of the jovian magnetotail, exiting on the northern dusk flank. For over three months, while covering a distance of $2000R_J$, the spacecraft measured a combination of iogenic ions and ionospheric plasma (indicated by H^+ and H_3^+ ions) flowing down the tail (McComas *et al.*, 2007a; McNutt *et al.*, 2007). The fluxes of both thermal and energetic particles were highly variable on time scales of minutes to days. The tailward fluxes of internally generated plasma led McComas and

Bagenal (2007) to argue that perhaps Jupiter does not have a complete Dungey cycle but that the large time scale for any reconnection flow (see Table 13.6) suggests that magnetic flux that is opened near the sub-solar magnetopause re-closes on the magnetopause before it has traveled down the tail. They suggested that the magnetotail comprises a pipe of internally generated plasma that disconnects from the planetary field and flows away from Jupiter in intermittent surges or bubbles, with no planetward Dungey return flow.

13.3 Saturn

Before the Cassini mission it was tempting to dismiss the magnetosphere of Saturn as merely a smaller, less exciting, version of the jovian magnetosphere. Cassini measurements of the particles and fields in Saturn's neighborhood have shown processes similar to those at Jupiter (e.g. satellite sources, ion pickup, flux tube interchange, corotation, etc) but they have also revealed substantial intriguing differences. The magnetosphere of Saturn is strongly dominated by neutral atoms and molecules. The number-density ratio of neutrals to ions is 15 : 1 in the Enceladus torus compared with 1 : 50 in the Io torus. In contrast with Jupiter's steady main aurora, Saturn's auroral emissions are strongly modulated by the solar wind. While one might expect the alignment of Saturn's magnetic axis with the planet's spin axis to produce an azimuthally symmetric magnetosphere, observations show an intriguing rotational modulation. But, more mysteriously, the rotational modulation is only observed in a limited region of the magnetosphere. The magnetosphere of Saturn is shown in Fig. 13.8. Below we provide a brief summary of current ideas about these topics, which are under active research as the Cassini spacecraft continues to orbit Saturn.

13.3.1 Plasma sources

One of the great discoveries of the Cassini mission to Saturn has been the active volcanism of the small icy moon Enceladus. While Enceladus is a mere one-seventh the size of Io, this small moon suffers tidal heating that drives the eruption of geysers from the south polar region. The geyser plumes, extending over 500 km from the surface, seem to be mostly ice particles with water vapor and minor quantities of molecular nitrogen, methane, and carbon dioxide (Porco *et al.*, 2006; Hansen *et al.*, 2006; Waite *et al.*, 2006). Enceladus' geysers eject water molecules at about one-third the rate of Io's neutral production (Hansen *et al.*, 2006) but few of the products become ionized. The nearly three orders of magnitude difference in the ion–neutral density ratios of the two magnetospheres can be been explained in terms of a much lower energy input into the Saturn system (Delamere *et al.*,

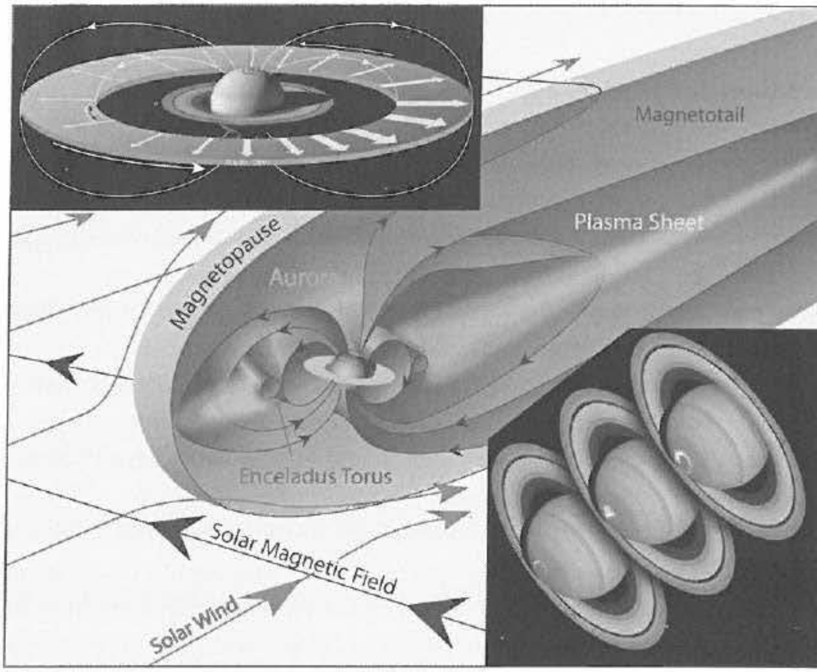

Fig. 13.8. (Center) Three-dimensional schematic representation of the magnetosphere of Saturn. (Top left) The asymmetric plasma disk; the arrows on the disk show the density and speed of the flow. The thin loops show the magnetic field. Gurnett (2007) proposed that the observed density variations are caused by a pattern of asymmetric radial outflows. (Bottom right) Hubble Space Telescope observations of Saturn's auroral emissions on 24, 26, and 28 January 2004 (Clarke, 2005).

2007). At Saturn the plasma flowing past Enceladus (at an orbital distance of ~ four saturnian radii) has a slower speed than the plasma flow past Io (at ~ six jovian radii). A factor 2 difference in relative motion (i.e. 26 km/s at Enceladus as against 57 km/s at Io) means that new ions pick up a factor 4 less energy. With less pickup energy the ions deliver less energy to the electrons. At low electron temperatures the ionization rates plummet and, correspondingly, plasma production drops. In fact, Delamere *et al.* (2007) showed that without an additional source of hot electrons (similar to that in the Io plasma torus) the Enceladus plasma torus would not be sustained.

The weaker plasma source at Saturn results in weaker centrifugal stresses and weaker magnetospheric currents. Thus the field structure at Saturn is similar to that shown in Fig. 13.6 for Jupiter but with less pronounced distortion from dipolar. The plasma pressure is also much reduced, so that Saturn's magnetosphere is less compressible that Jupiter's and shows a less dramatic response to changes in solar wind dynamic pressure.

13.3.2 Aurora at Saturn

Figure 13.8 shows Hubble Space Telescope (HST) images of Saturn's aurora (Clarke *et al.*, 2005). In contrast with Jupiter's large main auroral oval, which maps to regions deep inside the magnetosphere, Saturn's small auroral oval and strong variations in auroral intensity with solar wind conditions indicates that Saturn's aurora, like Earth's, marks the boundary of open and closed regions of magnetic flux. The picture was clarified during a campaign of combined Hubble and Cassini observations as the spacecraft approached Saturn in late 2000. For 22 days Cassini's instruments measured the magnetic field, plasma density, and plasma velocity in the solar wind while Hubble cameras and the Cassini radio antennas monitored Saturn's auroral activity. Nature cooperated and provided a couple of interplanetary shock waves that passed the Cassini spacecraft on 15 and 25 January 2001 and then hit the magnetosphere of Saturn some 17 hours later. Clarke *et al.* (2005) reported HST observations of the subsequent brightening of auroral emission, and Kurth *et al.* (2005) reported accompanying increases in radio emission. Crary *et al.* (2005) show a correlation of auroral intensity with solar-wind dynamical pressure, supporting the view that the solar wind has an Earth-like role at Saturn.

But further study showed that it was compression of the magnetopause by the solar wind that correlates with auroral intensity rather than reconnection of the solar and planetary magnetic fields. Crary *et al.* (2005) pointed out that, at Saturn's orbit, the solar magnetic field is essentially tangential so that the solar and planetary fields are largely orthogonal to each other: far from optimal conditions for magnetic reconnection. The magnetospheric processes driving Saturn's aurora should be better understood after Cassini moves to higher magnetic latitudes. In the mean time, the difficulties in measuring Saturn's rotation rate have wreaked havoc with our simple ideas of magnetospheric dynamics.

13.3.3 Planetary rotation at Saturn

So how do we establish how fast the interior of a gas planet is spinning? The usual trick is to measure the periodicity of radio emissions modulated by the planet's internal magnetic field. In this method it is assumed that the magnetic field is tilted and that the dynamo region where the field is generated spins at a rate representative of the bulk of the planet. Recent Cassini data indicate that apparent changes in Saturn's spin could in fact be caused by processes external to the planet. This raises new questions about how we measure and understand the rotation of the large gas planets. Saturn at first dumbfounded planetary theorists who study dynamo models by being observed to have a highly symmetric internal magnetic field. A field that is symmetric about the rotation axis violates a basic theorem of magnetic dynamos (Cowling, 1933). The second puzzle came with the detection of a systematic rotational modulation of the radio emission similar to a flashing strobe, which should not occur for a symmetric magnetic field. Meanwhile, radio measurements have revealed that Saturn's day appears to have become about 6 to 8 minutes longer – it is now roughly 10 hours and 47 minutes – since the 1980s when measured by the Voyager missions (Kurth *et al.*, 2007). Furthermore, the spin rate seems to keep changing and may be modulated by the solar wind speed (Zarka *et al.*, 2007).

A fundamental issue is whether the magnetospheric observations, including the radio emissions, do actually require the magnetic field emanating from the interior of Saturn to be asymmetric. Nearly 30 years ago, Stevenson suggested that strong shear motions in an electrically conducting shell surrounding the dynamo might impose symmetry around the rotational axis (Stevenson, 1981). That the rotational modulation of magnetospheric phenomena seems to be fairly constant with radial distance, that dynamic changes occur in the external plasma structures around Saturn, and that there is an apparent modulation by the solar wind speed indicate that an external explanation for Saturn's apparently erratic spin rate seems far more plausible than perturbations in the massive interior of the planet. Yet, localized magnetic anomalies (i.e. high-order multipoles) at high latitudes remain possible and may be affecting the currents that couple the magnetosphere to the planet (Southwood and Kivelson, 2007).

13.3.4 Magnetospheric dynamics

Gurnett *et al.* (2007) showed how Saturn's radio emission, the magnetic field measured in the magnetosphere, and the density of the plasma trapped in the magnetic field are all modulated with the same drifting period. They argued that the process that transports plasma radially outwards could be stronger on one side of Saturn than the other, as illustrated in the top left of Fig. 13.8. Gurnett *et al.* (2007) suggested that this circulation pattern also produces higher plasma densities in the region of stronger outflow and proposed that plasma production stresses the electrodynamic coupling between the magnetosphere and the planet, causing the pattern of weaker or stronger outward flow to slowly slip in phase relative to Saturn's internal rotation. What causes the proposed asymmetric convection pattern? In the 1980s, researchers tried to explain variations in the Io plasma torus (Dessler *et al.*, 1981) by invoking a convection pattern that rotated with the planet; however, evidence of such a flow pattern in the jovian magnetosphere remains elusive. Alternatively, a system of neutral winds in Saturn's atmosphere could drag the ionosphere around, which would stir up the magnetosphere electrodynamically and provide a source of hot electrons. Could small variations in the high-energy electron population in the Enceladus torus, similar to those in the Io torus, be causing the dramatic changes in plasma density observed by Cassini? If so, large-scale convection patterns in the magnetosphere may not be necessary, just minor modulations in the electrical currents that flow along the magnetic field between the equatorial plasma disk and the planet's ionosphere, bringing small fluxes of ionizing high-energy electrons to the torus. Delamere and Bagenal (2008) showed that a modulation in the small hot-electron population could produce the factor-2 variation in plasma density observed by Cassini.

Undoubtedly, the issue of Saturn's rotation rate and its coupling to the magnetosphere will be a vital area of exploration over the next few years. Similarly, it will be important to investigate whether material is ejected down the tail in the manner and to the extent of the jovian system. Only a few plasmoids have been detected to date at Saturn but this may be a result of limited coverage by the Cassini spacecraft. The substantial polar cap, marked by the aurora, and the influence of the solar wind on the auroral intensity indicate that the Dungey reconnection cycle plays a substantial role at Saturn. The extent and mechanism whereby any return, planetward, flow operates in the magnetotail awaits further exploration.

13.4 Uranus and Neptune

The Voyager fly-bys of Uranus (1986) and Neptune (1989) revealed what have to be described as highly irregular magnetospheres. The non-dipolar magnetic fields and the large angle between the magnetic and rotation axes not only pose interesting problems for dynamo theorists but also challenge the ideas of magnetospheric dynamics. Unfortunately, little study has been made of these odd magnetospheres for the past 15 years and there is little hope of further exploration in the foreseeable future. Thus, there is not much to add to the comparative reviews of their fields by Connerney (1993) and of their magnetospheres by Bagenal (1992). Here we provide a brief précis of these reviews to which the reader should turn for original references.

Tables 13.2 and 13.3 as well as Fig. 13.1 show Uranus and Neptune to have substantial magnetospheres that envelope most of their satellites. Figure 13.2 gives a sense of the irregularity of their magnetic fields, approximated as large tilts and offsets. Table 13.6 tells us that from just the solar wind and planetary parameters we should expect both rotation and solar wind coupling to affect the dynamics of these magnetospheres (though the weak IMF of the outer heliosphere suggests that reconnection will be much weaker than at planets closer to the Sun). Next, we take the orientations of these planets' magnetic fields shown in Fig. 13.2 and consider how these configurations, which rotate about the planet's spin axis every

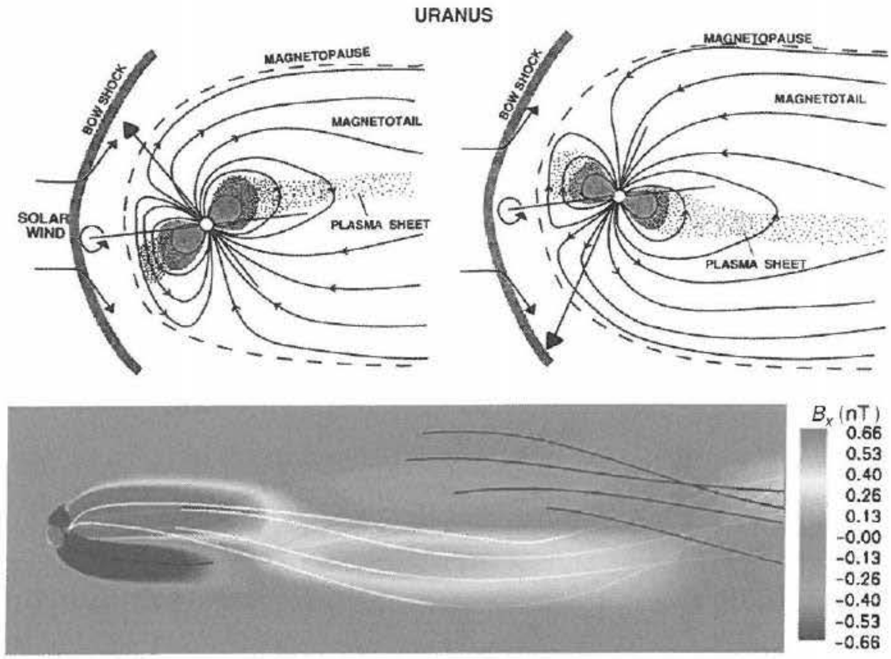

Fig. 13.9. The magnetosphere of Uranus at solstice (the time of the Voyager 2 flyby). The upper left and right panels show the configuration at different phases of the planet's 18-hour spin period (Bagenal, 1992). The lower panel shows a numerical simulation of the helical magnetotail (Tóth *et al.*, 2004). See also the color-plate section.

16–17 hours, might affect the solar wind coupling process illustrated in Figure 13.4. For Uranus around solstice (the Voyager era of the mid 1980s), when the spin axis is pointed roughly towards the Sun, the large tilt of the magnetic axis will result in a magnetosphere that to first approximation resembles that of the Earth but revolves every 17 hours. The finite propagation (at the Alfvén speed) of this rotational modulation down the magnetotail produces a helical plasma sheet and braided lobes of oppositely directed magnetic field (Fig. 13.9). At Neptune, the planet's obliquity being similar to Earth and Saturn one might have expected the fairly simple configurations of either of those planet's magnetospheres. But the large tilt angle discovered by Voyager results in a configuration that changes dramatically (the tail current sheet changes from a plane to a cylinder) over the 16 hour rotation period (Fig. 13.10).

The large range of the "solar wind angle" (see the last row of Table 13.3) indicates that substantial changes in orientation of the planet's spin with respect to the radial direction of the solar wind occur over the (long) orbital periods of these planets. Thus, one has the interesting challenge of imagining how the

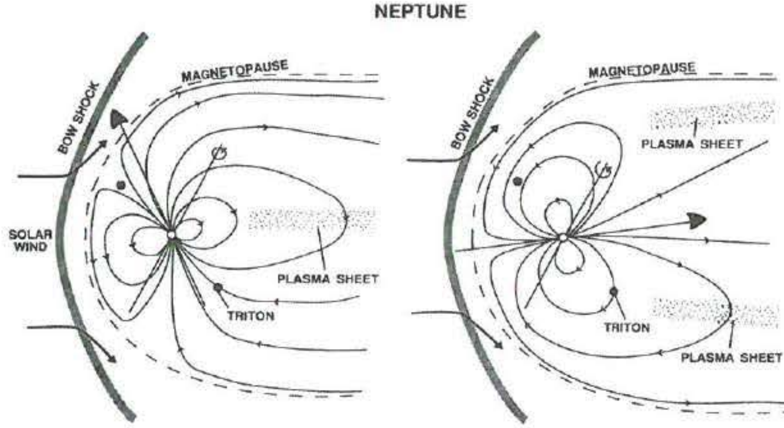

Fig. 13.10. The magnetosphere of Neptune in the configuration corresponding to the time of the Voyager 2 fly-by (Bagenal, 1992). Over the 19-hour spin period the magnetospheric plasma sheet in the tail changes from roughly planar to cylindrical.

magnetosphere of Uranus was behaving during equinox in 2007, when the spin axis was perpendicular to the solar wind direction (and parallel or anti-parallel to the IMF direction). Unfortunately we are unlikely to have any measurements to test the output of our imaginations. Such speculations are not wasted, however, since it is quite possible that such configurations – and many others – could have occurred in earlier epochs of Earth's history (as modeled by Zieger *et al.*, 2004) or may now be occuring in any of the giant planets detected in other solar systems.

13.5 Mercury and Ganymede

The smallest objects with internal dynamos are Mercury and Ganymede. These mini-magnetospheres were recently reviewed by Kivelson (2007). The small innermost planet and the solar system's largest moon are about the same size and both are believed to have iron cores. Approximately dipolar magnetic fields have been detected; these hold off the surrounding plasma flow to make small but distinct magnetospheres. Just two brief fly-bys by Mariner 10 in the early 1970s gave a glimpse of Mercury's magnetosphere (see the review by Slavin, 2004). These early observations revealed a magnetosphere that, while small, seemed to have most of the main properties observed at Earth (Fig. 2.7), including trapped energetic-particle populations, mini-substorms, and particle injections from the magnetotail, which seem roughly consistent with simple magnetospheric scaling laws. The anticipated arrival of the MESSENGER spacecraft in 2011 and the future launch of the Bebi Colombo mission have provoked further thought about this largely forgotten little magnetosphere and we shall soon see if the details match up to expectations.

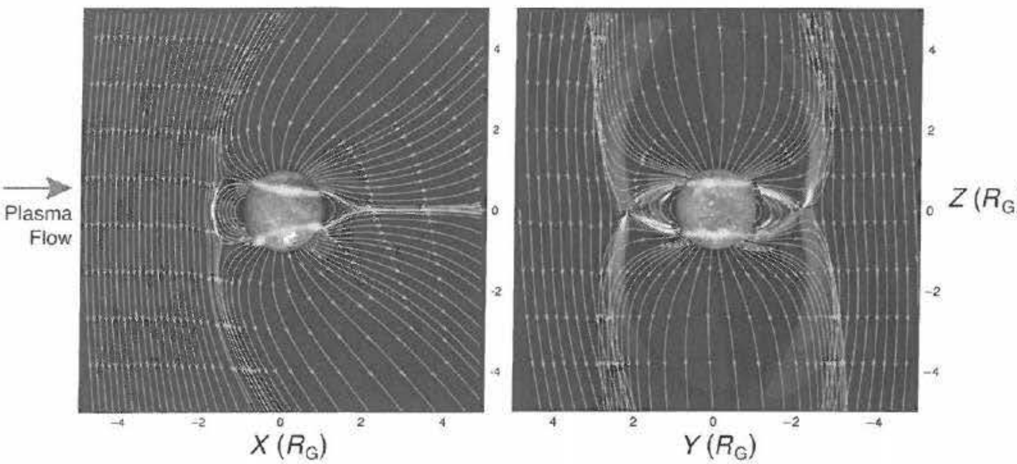

Fig. 13.11. Numerical model of the magnetosphere of Ganymede, with the satellite and the location of the auroral emissions superimposed (based on Jia *et al.*, 2008). (Left) The view looking at the anti-Jupiter side of Ganymede. (Right) The view looking in the direction of the plasma flow at the upstream side (orbital trailing side) of Ganymede, with Jupiter to the left. The shaded areas show the regions of currents parallel to the magnetic field. See also the color-plate section.

Ganymede's magnetosphere sits deep within the magnetosphere of Jupiter (for the background and discussion of Galileo observations see Kivelson *et al.*, 2004). Unlike the supersonic flows of the solar wind, the magnetospheric plasma impinging on Ganymede is subsonic and sub-Alfvénic. There is no upstream bow shock, therefore, and the flowing magnetospheric plasma convects Jupiter's magnetic field, which is roughly anti-parallel to that of Ganymede, towards the upstream magnetopause. The net result is a unique magnetospheric configuration with a region near the equator of magnetic flux that closes on the moon and with polar magnetic flux that connects the moon to Jupiter's north and south ionospheres (Fig. 13.11). A Dungey-style reconnection cycle seems to operate: upstream reconnection opens previously closed flux, convects flux tubes over Ganymede's pole, and re-closes the flux downstream. Computer simulations are helpful in visualizing the process (Jia *et al.*, 2008) but lack of information about the conductivities of Ganymede's tenuous patchy atmosphere and icy surface limit our understanding of the circuit of electrical currents that couple the magnetosphere to the moon.

13.6 Objects without dynamos

Having discussed the seven objects that have internally generated magnetic fields, we return to the objects without dynamos. As summarized in Table 13.1, the nature of the interaction between such bodies and the plasma in which they are embedded depends on the Mach number of the surrounding flow but is determined principally by the electrical conductivity of the body. If conducting paths exist across the planet's interior or ionosphere then electric currents flow through the body and into the surrounding plasma, where they create forces that slow and divert the incident flow.

In the case of an object sitting in the supersonic solar wind, the flow diverts around a region that is similar to a planetary magnetosphere. Mars and Venus have ionospheres that provide the required conducting paths. The barrier that separates planetary plasma from solar wind plasma is referred to as an ionopause (and is analogous to a magnetopause). Earth's Moon, with no ionosphere and a very low conductivity surface, does not deflect the bulk of the solar wind incident on it. Instead, the solar wind runs directly into the surface, where it is absorbed. The absorption leaves the region immediately downstream of the Moon in the flowing plasma (the wake) devoid of plasma, but the void fills in as solar wind plasma flows towards the center of the wake.

When the flow impinging on an object is subsonic, no upstream shock forms. But the flow will be absorbed or diverted depending on whether electrical currents flow within the object or within its ionosphere and into the surrounding plasma. Objects interacting with subsonic flow are exemplified by Io; similar processes occur, albeit to a lesser extent, at Enceladus, Titan, Triton, Europa, and several satellites embedded in the giant planet magnetospheres.

13.6.1 Venus and Mars

The magnetic structure surrounding Mars and Venus is similar to that around magnetized objects, because the interaction causes the magnetic field of the solar wind to drape around the planet. The draped field stretches out downstream (away from the sun), forming a magnetotail (Fig. 13.12). The symmetry of the magnetic configuration within such a tail is governed by the orientation of the magnetic field in the incident solar wind, and that orientation changes with time. For example, if the interplanetary magnetic field (IMF) is oriented northward then the symmetry plane of the tail is in the the east–west direction, and the northern lobe field points away from the sun while the southern lobe field points towards the sun. A southward-oriented IMF would reverse these polarities, and other orientations would produce rotations of the tail's plane of symmetry.

The solar wind brings in magnetic flux tubes that pile up at high altitudes at the dayside ionopause where, depending on the solar wind's dynamic pressure, they may either remain for extended times, thus producing a magnetic barrier that diverts the incident solar wind, or penetrate to low altitudes in localized bundles. Such localized bundles of magnetic flux are often highly twisted structures stretched out along the direction of the magnetic field. Such structures, referred to as flux

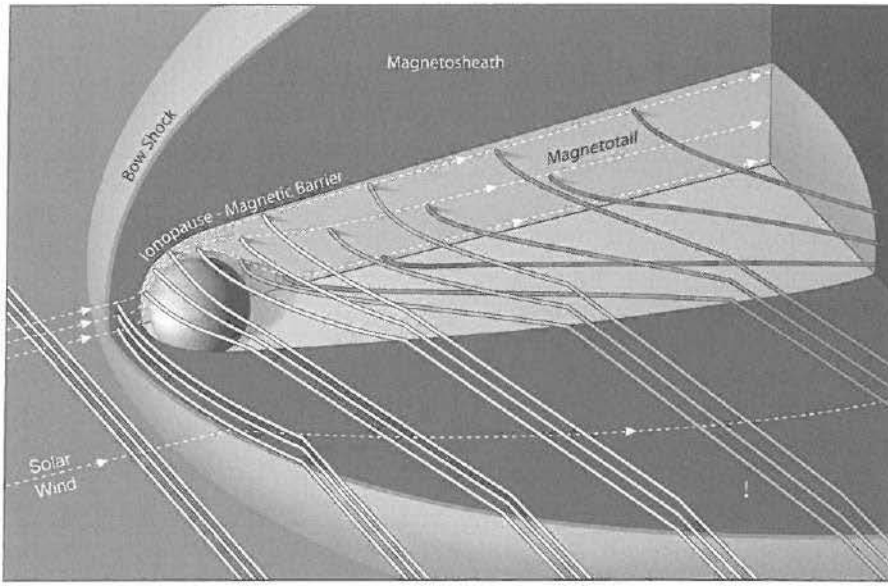

Fig. 13.12. The draping of tubes of solar magnetic flux around a conducting ionosphere such as that of Venus. The flux tubes are slowed down and sink into the wake to form a tail (after Saunders and Russell, 1986).

ropes, are discussed in Chapter 6. These flux ropes may be dragged deep into the atmosphere, possibly carrying away significant amounts of atmosphere.

While Mars' remarkably strong remanent magnetism extends its influence > 1000 km from the surface (Brain *et al.*, 2003), the overall interaction of the solar wind with Mars is more atmospheric (Nagy *et al.*, 2004) than magnetospheric. Mars interacts with the solar wind principally through currents that link to the ionosphere, but there are portions of the surface over which local magnetic fields block the access of the solar wind to low altitudes (Fig. 13.13). It has been suggested that "mini-magnetospheres" extending up to 1000 km form above the regions of intense crustal magnetization in the southern hemisphere; these mini-magnetospheres protect portions of the atmosphere from direct interaction with the solar wind. As a result, the crustal magnetization may have modified the evolution of the atmosphere and may still modify energy deposition into the upper atmosphere.

Several processes involved in the solar wind interaction could have contributed to atmospheric losses at Venus and Mars (Fig. 13.13). The outer neutral atmospheres of Venus and Mars extend out into the solar wind where neutral atoms are photoionized and carried away by the solar wind. Newly ionized ions pick up substantial energy and correspondingly large gyroradii. These energetic ions bombard the upper atmosphere, causing heating and ionization. At times of particularly

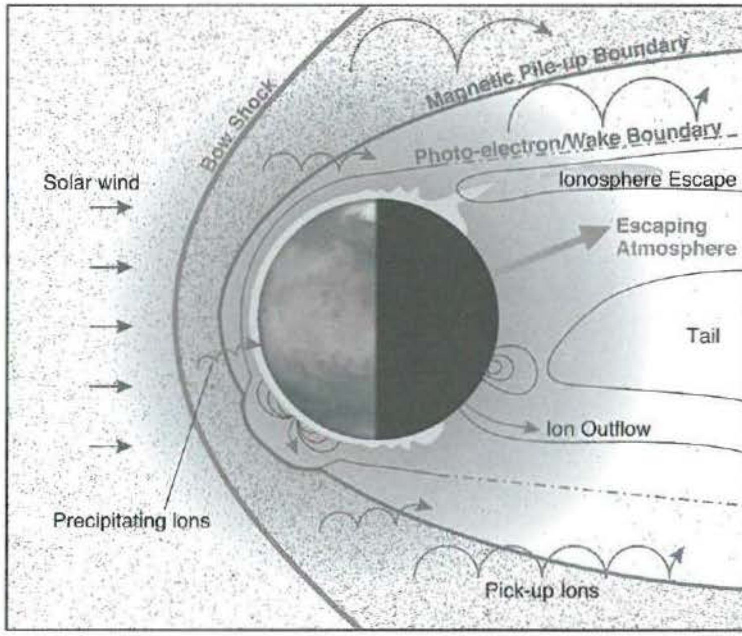

Fig. 13.13. Interaction of the solar wind with the atmosphere, ionosphere, and magnetized crust of Mars. The several processes whereby the planet may have lost much of its atmosphere are shown.

high solar wind pressure the ionosphere can be stripped away in the solar wind. Fresh ionization in the upstream solar wind also generates plasma waves. The solar wind convects the plasma waves towards the planet and into the upper layers of the ionosphere; it is possibly funneled by localized magnetic fields, in the case of Mars, that heat the ions and drive ion outflows, in a similar way to processes in the polar regions at Earth. Quantitative analyses of these different processes, both currently occurring and in the past, are active areas of research and the scientific targets of future missions to Mars.

13.6.2 Io

The discovery of Io's broad influences on the jovian system predated spacecraft explorations. Bigg (1964) discovered Io's controlling influence over Jupiter's decametric radio emissions. Brown and Chaffee (1974) observed sodium emission from Io, which Trafton *et al.* (1974) soon demonstrated to come from extended neutral clouds and not Io itself. Soon thereafter, Kupo *et al.* (1976) detected emissions from sulfur ions, which Brown (1976) recognized as coming from a dense plasma. With the prediction of volcanism by Peale *et al.* (1979) just before its discovery by Voyager 1 (Morabito *et al.*, 1979), a consistent picture of Io's role began to emerge.

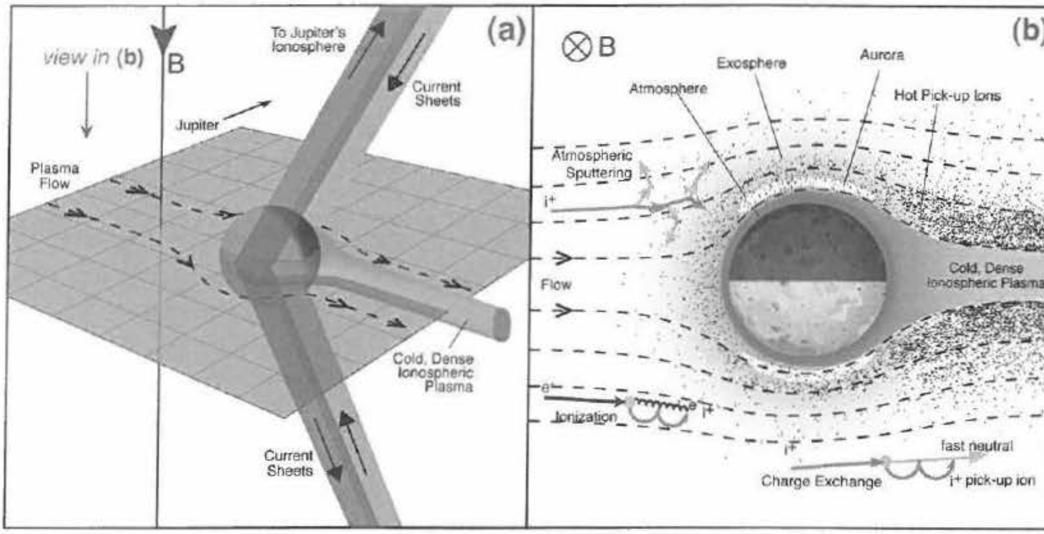

Fig. 13.14. Two views of the interaction between Io and the plasma torus. (a) A three-dimensional view showing the current sheets that couple Io and the surrounding plasma to Jupiter's ionosphere. (b) Cross section of the interaction looking down on the north pole of Io, in the plane of Io's equator, when Io is located between the Sun and Jupiter (orbital phase 180°, local noon in magnetospheric coordinates).

Voyager 1's discovery of Jupiter's aurora and extreme UV emission from the torus (Broadfoot *et al.*, 1979), along with its in situ measurements of the magnetosphere, extended our awareness of Io's effect on the larger system.

The ensuing 25 years of observation by interplanetary missions, Earth-orbiting observatories, and ground-based telescopes has deepened our understanding of Io's influences (see the reviews by Thomas *et al.*, 2004, and Schneider and Bagenal, 2007). Highlights include Galileo's many close fly-bys of Io, with detailed fields-and-particle measurements of Io's interaction with the magnetosphere, and Cassini's months-long UV observation of the torus. Progress from Earth-based studies include the Hubble Space Telescope's sensitive UV observations of the footprint aurora and of Io's atmospheric emissions and ground-based observations of new atomic and molecular species in Io's atmosphere and the plasma torus.

Over the age of the solar system, the tonne/s loss of Iogenic material to the magnetosphere accumulates to a net decrease in radius of about 2 km. While this loss is significant, Io is not in danger of running out of SO_2 in the life time of the solar system. It is plausible, however, that other volatile species such as H_2O were originally present on Io but were completely lost early in its history through processes now depleting Io of SO_2.

Figure 13.14 presents a sketch of the interaction of Io with the surrounding plasma that illustrates some of the processes. Inelastic collisions of torus ions with Io's atmosphere heat the atmospheric gases, causing a significant population of neutral molecules and atoms to gain speeds above Io's 2.6 km/s gravitational escape speed. These neutrals form an extensive corona circling most of the way around Jupiter. Io loses about 1–3 tonnes of neutral atoms per second. How much of the neutral escape is in molecular form (SO_2, SO, or S_2) as against atomic O or S is not known.

The various ion–electron–atom interactions each have a key effect on the magnetosphere. Most importantly torus ions collide with neutral atoms in the atmosphere, which in turn collide with other atoms in the process known as sputtering. Typically, one torus ion can transfer enough momentum for several atmospheric atoms or molecules to be ejected into Io's corona or possibly to escape from Io altogether. This is the primary pathway for material to be supplied to the neutral clouds and ultimately to the plasma torus. A second key reaction is electron impact ionization: a torus electron ionizes an atmospheric atom, which is then accelerated up to the speed of the plasma and leaves Io. Torus ions can also charge-exchange with atmospheric neutrals, which results in a fresh ion and a high-speed neutral. Elastic collisions between ions and atoms can also eject material at speeds between those resulting from sputtering and charge exchange. Finally, electron-impact dissociation breaks down molecules into their component atoms.

Figure 13.14 shows that the strong magnetic field of Jupiter affects the interaction in such a way that the flow around Io resembles fluid flow around a cylinder. (Note that a strong intrinsic magnetic field at Io has been ruled out by Galileo fly-bys over the poles.) Io's motion through the plasma creates an electrical current. While its surface or interior may be modestly conducting, the current is more likely to be carried in other conducting materials surrounding Io, such as its ionosphere and the plasma produced by ionization of its neutral corona. Currents induced across Io are closed by currents that flow along field lines between Io and Jupiter's polar ionosphere in both hemispheres. Observations by the Voyager 1 and Galileo spacecraft indicate that the net current in each circuit is about three million amps. The relative contributions from the conduction current through Io's ionosphere and the current generated by ion pickup in the surrounding plasma remains an issue of debate that awaits more sophisticated models (e.g. see the review by Saur *et al.*, 2004).

A major question regarding Jupiter's magnetosphere is whether most mass loading happens in the near-Io interaction or in the broad neutral clouds far from Io. There is no doubt that substantial pickup occurs near Io, simply owing to the exposure of the upper atmosphere to pickup by the magnetosphere. Pickup near Io is also supported by evidence of fresh pick-up ions of molecules (SO_2^+, SO^+, S_2^+, H_2S^+) near Io with dissociation lifetimes of just a few hours. But a closer look shows that the bulk of the Iogenic source comes from the ionization of atomic sulfur and oxygen farther from Io. Galileo measurements of the plasma fluxes downstream of Io suggest that the plasma source from the ionization of material in the immediate vicinity (within $\sim 5R_{Io}$) of Io is less than 300 kg/s, which is $\sim$ 15% of the canonical net tonnes-per-second Iogenic source. The remainder must come from ionization of the extended clouds. It is not clear whether the observations were made during a typical situation, nor it is well established how much the net source and relative contributions of local and distant processes vary with Io's volcanic activity.

While most impacting plasma is diverted to Io's flanks, some is locked to field lines that are carried through Io itself. This $\sim$ 10% of upstream plasma is rapidly decelerated and moves slowly ($\sim$ 3–7 km/s) over the poles. Most particles are absorbed by the moon or its tenuous polar atmosphere, so that the almost-stagnant polar flux tubes are evacuated of plasma. Downstream of Io, the Galileo instruments detected a small trickle of the cold dense ionospheric plasma that had been stripped away. This cold dense "tail" had a dramatic signature ($>$ ten times the background density) but the nearly stagnant flow ($\sim$ 1 km/s) means that the net flux of this cold ionospheric material is at most a few percent of the Iogenic source and quickly couples to the surrounding torus plasma (Delamere *et al.*, 2003).

The strong electrodynamic interaction generates Alfvén waves that propagate away from Io along the magnetic field (reviewed by Saur *et al.*, 2004). Other MHD modes that propagate perpendicularly to the field dissipate within a short distance. The intense auroral emission in Jupiter's atmosphere at each "foot" of the flux tube connected to Io tells us that electrons are accelerated somewhere between Io and the atmosphere. The strong correlation of decametric radio emissions with Io's location also tells us that electrons stream away from Jupiter along the Io flux tube and field lines downstream of Io. But how much of the Alfvén wave energy propagates through the torus and reaches Jupiter is not known. Magnetohydrodynamic models suggest that much of the wave energy is reflected at the sharp latitudinal gradients of density in the torus. Furthermore, how the Alfvén wave evolves as it moves through the very low density region between the torus and Jupiter's ionosphere is far from understood. Early ideas suggested that multiple bounces of the Alfvén wave between ionospheres of opposite hemispheres could explain the repetitive bursts of radio emission. More recent studies suggest that the process is more complex, however. Ergun *et al.* (2006) suggested that a resonance is set up whereby Alfvén waves reaching Jupiter's ionosphere accelerate electrons responsible for the short bursts of radio emission (S-bursts). As flux tubes are carried downstream of Io a steady-state current system is set up (Su *et al.*, 2003, 2006). In upward current regions, a few R_J above the ionosphere, potential drops develop that accelerate electrons into the ionosphere to produce the wake aurora (Fig. 13.7).

13.7 Outstanding questions

The tables presented in this chapter quantify the characteristics of the seven magnetospheres of our solar system. The schematics give a glimpse of the diversity of their natures. While magnetospheres must share the same underlying basic physical processes, it is the application to very different conditions at the different planets that makes the study of planetary magnetospheres so interesting and tests our understanding. Below are major outstanding questions in planetary magnetospheres.

- How do magnetic dynamos work in the wide range of planetary objects? Why do tiny Mercury and Ganymede have magnetic fields while Earth's sister planet Venus does not? What do the irregular magnetic fields of Uranus and Neptune tell us about their interiors?
- At Saturn, what causes the spin-periodic variability in radio emissions, magnetic field, and plasma properties? What causes the apparent fluctuation in the periodicity?
- How is plasma heated as it moves radially outward in rotation-dominated magnetospheres?
- How is material lost down the magnetotails of Jupiter and Saturn?
- What causes the ~ three-day periodicity in particle fluxes in the magnetosphere of Jupiter?
- Do Jupiter and/or Saturn have return, planetward, Dungey flows in the magnetotails? If not, how do flux tubes opened by dayside reconnection close and conserve magnetic flux?
- What processes lead to the decoupling of the middle magnetosphere of Jupiter from the planet's rotating ionosphere and cause the narrow auroral oval? What role do parallel potential drops play?
- What processes relate the solar wind variability to the apparent changes in Saturn's main aurora and the polar aurora at Jupiter?
- How do electrical currents couple the magnetospheres of Ganymede and Mercury to these planets with very tenuous atmospheres?
- How are particles accelerated and trapped in the mini-magnetospheres of Ganymede and Mercury?
- What processes have been responsible for removing atmospheric gases (particularly water) over the geological history of Mars and Venus?
- What processes are involved in the interactions of Io and Enceladus with their surrounding plasmas? What causes the similarities and differences between the two systems?