THE CURRENT SYSTEMS OF THE JOVIAN MAGNETOSPHERE AND IONOSPHERE AND PREDICTIONS FOR SATURN

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Abstract. Magnetized plasmas in motion inevitably generate currents and the magnetized plasmas that form the magnetospheres of the outer planets are no exception. Although a focus on the current systems tends to distract from the underlying dynamics, many elements of magnetospheric structure can be organized by discussing them in terms of the large scale currents present in the system. This paper starts with a digression on the pitfalls of a current-based description of a planetary magnetosphere but then proceeds to characterize the magnetospheres of Jupiter, Earth, and to some extent Saturn by the currents that flow within them. Emphasis is placed on the field-aligned currents that couple the equatorial magnetospheres to the ionospheres and the conditions that call for the development of field-aligned electric fields.

Keywords: outer planets, magnetosphere, ionosphere, current systems

1. Introduction

In discussions of the magnetospheres of Earth and other planets, it is common to identify large scale current systems that account for the observed plasma and magnetic structure. In discussions of the terrestrial magnetosphere, we talk of the Chapman-Ferraro currents that flow on the magnetopause, the tail current sheet that separates the northern and southern lobes of the magnetotail, the Region 1 and Region 2 currents that link the ionosphere to other parts of the large scale system, the ring current that forms at times of geomagnetic activity, and the substorm currents that link the equatorial plasma to the auroral zones of the ionosphere where they create both beauty and havoc in the upper atmosphere. It seems natural to believe that with currents establishing magnetospheric structure, an electric field is responsible for the plasma motions through the familiar "frozen-in field" picture of magnetohydrodynamics using the relation $\mathbf{u} = \mathbf{E} \times \mathbf{B}/B^2$. Here $\mathbf{u}$ is the bulk flow velocity and $\mathbf{E}$ ($\mathbf{B}$) is the electric (magnetic) field. This approach is referred to as the $E - j$ description.

It seems reasonable, then, that a compendium of papers on the outer planets should include a paper describing and contrasting the current systems that characterize the giant planets Jupiter and Saturn, and indeed that is the topic of this chapter. There is, nonetheless, a powerful caveat that must be considered, so Sec-

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tion 2 addresses the objections to an $E - j$ description of a magnetosphere as discussed by Parker (1996; 2000).

Magnetohydrodynamics (MHD) tells us that changing flows, pressure gradients, or inertial stresses generate currents. For example, an azimuthal current develops in Jupiter's equatorial plasma at all local times in response to centrifugal stresses. Also heavy ions from Io diffuse outward and the plasma flow slows below corotation speed. Slowing is greatest near the equator, causing the magnetic field lines to curl backward if the magnetic flux is frozen into the plasma motion. The curl of B implies an additional current in the radial direction that closes at its inner and outer boundaries through field-aligned currents linking the equatorial currents to Jupiter's ionosphere. The ultimate source of the radial current is the shear in the azimuthal flow. Surface currents flow on the magnetopause in response to the change of pressure of the plasma across the boundary.

The magnetosphere also responds to temporal variations, whether the source of the variation is internal or external. There is a direct link between the changes of flow and changes of the currents that control the magnetic configuration. Examples of current systems arising from changing flows are familiar from Earth. During substorms, bursty bulk flows (Angelopoulos *et al.*, 1992; 1997; Baumjohann *et al.*, 1990) and other substorm-related flows (Lyons *et al.*, 1999) drive currents into the auroral ionosphere where they can be observed as brightenings. At Jupiter (and surely at Saturn) the interactions of the moons with magnetospheric plasma drives currents, once again linked to changing the plasma flow. One doesn't have to talk about "generators" and "loads". If the flow is dynamic, or if special pressure gradients are present, currents naturally arise (current is generated). The current flows to a part of the system where it is dissipated as it acts to change the motion of the remote plasma.

Plasma currents require current carriers. If there are not enough current carriers (usually electrons) to carry the current, either the available electrons must be accelerated or additional electrons must be sucked out of a source region. This is why field-aligned electric fields develop. We are lucky that such electric fields develop because electrons accelerated by $\mathbf{E}$ "light up" the auroral ionosphere and give us indirect evidence of where currents are flowing. The aurora is therefore an important tool in a study of currents.

In the following sections, the currents important at Jupiter and Earth are described. In many ways, Saturn is likely to be more similar to Earth than to Jupiter, but we can learn about both Earth and Saturn by examining phenomena that may be subtle at Earth (or Saturn) but appear in extreme form at Jupiter and we can consider what parallels are likely to be found at Saturn.

2. Currents: Inconveniences and Caveats

The topic of this chapter is currents, but Parker warns us (1996; 2000) that analysis starting from currents is at the very least intractable and often misleading. Why? Underlying our analysis are Newton's laws and Maxwell's equations (simplified for MHD limit in which scales are large compared with gyroradii, etc.). Fields and flows are related through

$$\frac{\mathrm{d}\,(\rho \mathbf{u})}{\mathrm{d}t} = -\nabla \cdot \tilde{\mathbf{P}} + \mathbf{j} \times \mathbf{B} \,. \tag{1}$$

Here ρ is the mass density, $\tilde{\mathbf{P}}$ the pressure tensor and $\mathbf{j}$ is the current density. In the MHD limit, currents are determined by the magnetic field structure through

$$\mathbf{j} = \nabla \times \mathbf{B}/\mu_0 \,. \tag{2}$$

Equation (2) can be inverted to give $\mathbf{B}$ in terms of $\mathbf{j}$ but only through a highly non-local and mathematically complex relationship

$$\mathbf{B}\,(\mathbf{r}) = \frac{\mu_0}{4\pi} \overset{\text{all space}}{\iiint} \mathrm{d}\mathbf{r}' \; \frac{\mathbf{j}\left(\mathbf{r}'\right) \times \left(\mathbf{r} - \mathbf{r}'\right)}{|\mathbf{r} - \mathbf{r}'|^3} \tag{3}$$

that can lead into a morass. We must know $\mathbf{j}$ everywhere in order to determine $\mathbf{B}$. Everywhere is not an exaggeration. Even very distant currents may matter. For example, an infinite plane current sheet generates a field perturbation that is independent of distance from the sheet! The current flowing on the dayside magnetopause (a large if not infinite current sheet) can therefore not be neglected if one proposes to determine $\mathbf{B}$ anywhere in the equatorial magnetosphere inside of $10R_\mathrm{E}$. Yet global knowledge of $\mathbf{j}$ at an instant of time, essential to an accurate determination of $\mathbf{B}$, is not provided by spacecraft measurements. On the other hand, strictly local measurements of $\mathbf{B}$ can be obtained by a small number of closely spaced spacecraft such as those that comprise the Cluster mission (Escoubet *et al.*, 2001), and such measurements provide an excellent approximation to the local $\mathbf{j}$ through Equation (2), a much more convenient situation.

Researchers particularly like to think about currents because they feel comfortable with circuit analogies. However, circuit analogies must be treated with caution. Circuits provide useful insight when we wish to consider how different parts of the system are linked and they are often used to infer "what drives what." But Parker warns: "Electric circuit equations are not derived. They are declared by casual analogy between the time dependent net current in the magnetic field and the current in a fixed electric circuit in the laboratory." And there are several possible pitfalls in circuit analysis. For example, because plasmas at rest can be thought of as electrically neutral, it is acceptable to assume $\nabla \cdot \mathbf{j} = 0$, as is normally done when analyzing circuits. However, this assumption applies strictly only in the plasma rest frame. In frames with finite charge density ρ_q there is no guarantee that

j is divergenceless. The transformations to a frame moving with velocity $u \ll c$ (the velocity of light) are given by

$$\mathbf{E}' = \mathbf{E} + \mathbf{u} \times \mathbf{B}/c; \qquad \mathbf{B}' = \mathbf{B} \tag{4}$$

$$\rho_q' = \rho_q - \mathbf{u} \cdot \mathbf{j}/c^2; \qquad \mathbf{j}' = \mathbf{j} - \mathbf{u}\rho_q \tag{5}$$

where the Gaussian system is used for clarity of the argument. In the plasma rest frame,

$$\mathbf{E}' = 0; \quad \rho_q' = 0; \quad \nabla \cdot \mathbf{j} = 0\ . \tag{6}$$

In the frame moving at velocity **u**,

$$\rho_q = \mathbf{u} \cdot \mathbf{j}/c^2\ . \tag{7}$$

The continuity equation, a frame-independent relationship requires

$$\nabla \cdot \mathbf{j} + \partial \rho_q/\partial t = 0 \tag{8}$$

and correspondingly

$$\nabla \cdot \mathbf{j} + \mathbf{u} \cdot \partial \mathbf{j}/\partial t/c^2 = 0\ . \tag{9}$$

For spatial scales and flow speeds typically found in the terrestrial magnetosphere, the right side is very much smaller than the individual terms on the left side but it may not be negligible in all space plasmas.

A more pertinent concern in using circuit analogies is that coupling between the magnetosphere and the ionosphere is described as if the current diverted from equatorial paths flows strictly along field lines and into the ionosphere. Yet nothing constrains the current to remain on a flux tube. Indeed flux tubes may well “leak” current. The point is illustrated in Figure 1. In (a), the current flows onto the flux tube near the equator, flows along the field and diverges in the ionosphere. In (b), the current flows onto the flux tube as for (a), but flows off in a distributed manner so that only a small fraction of the equatorial current reaches the ionosphere. Circuit analogies don’t consider this possibility!

Another oversimplification is found in cartoons such at that of the familiar McPherron substorm current wedge illustrated in Figure 2 (McPherron, 1991). Wire circuits can bend sharply, changing the direction of the current abruptly. The tail current does not discontinuously change direction thereafter remaining guided along a flux tube from equator to ionosphere (nor does it flow in extremely thin sheets).

So, there are many reasons not to address the properties of planetary magnetospheres by describing the current systems that they contain, but I shall cheerfully ignore all the good advice just given. In conclusion of this digression and in advance of overlooking all of its sensible warnings, I recommend reading Parker’s papers on the subject.

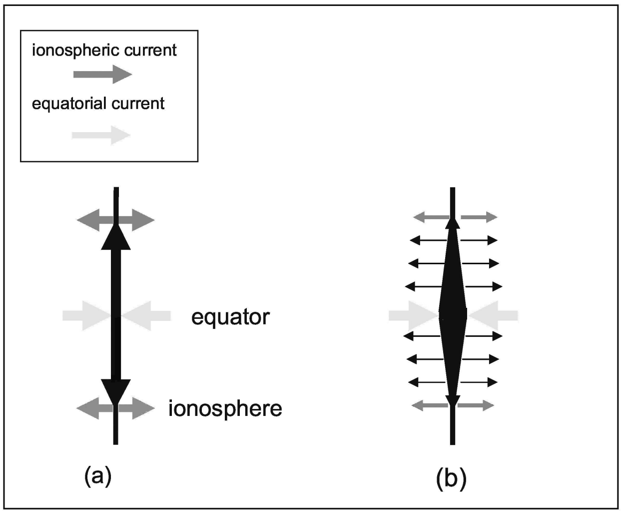


Figure 1. Currents linking magnetosphere and ionosphere. (a) currents confined to flux tube, (b) currents diverge from flux tube between equator and ionosphere.

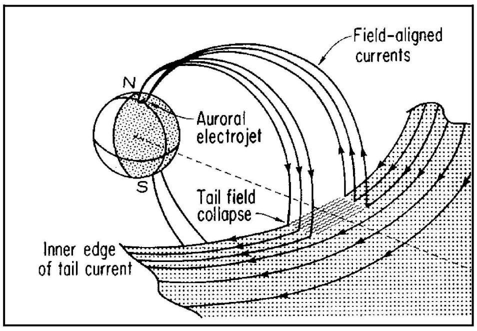


Figure 2. Substorm current wedge as discussed by McPherron (1991).

3. Large Scale Current Systems at Jupiter and Saturn

Most of the large scale current systems at Jupiter or Saturn have analogues at Earth. In all of the magnetospheres, the magnetic field is largely confined within a cavity in the solar wind by interaction of field and flow. The confinement drives surface current on the magnetopause, the magnetopause current. In the magnetotail, the surface current closes through a tail current sheet. Figure 3 shows schematically a cross-section through the magnetotail in which the current closing above and below flows on the magnetopause and returns through the center of the magnetotail.

The magnetopause and tail currents, shown here for Earth, are reversed at Saturn or Jupiter because of the different dipole orientations. The ring current, carried by energetic particles, has no direct analogy at Jupiter.

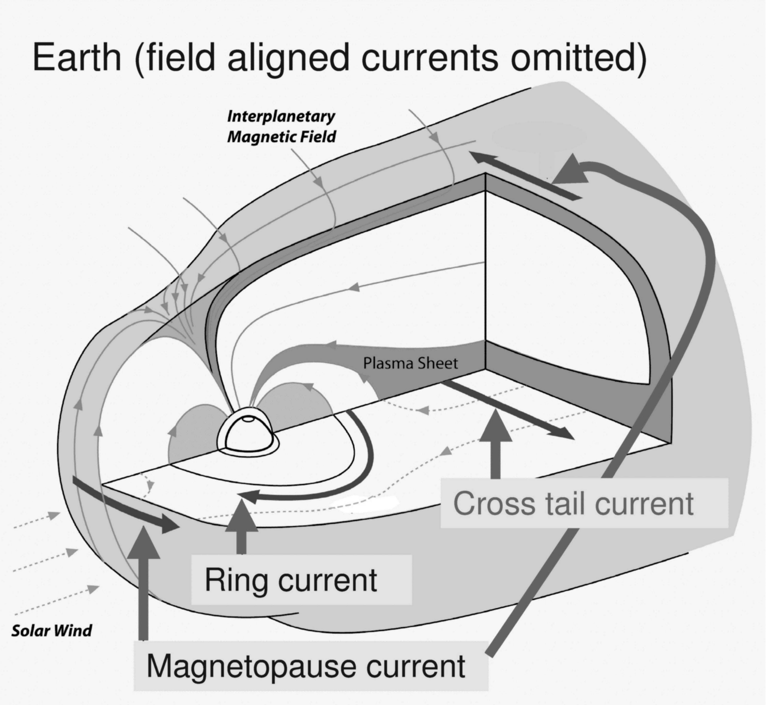


Figure 3. Schematic of currents in the terrestrial magnetosphere (courtesy of K. Khurana, 2004).

TABLE I

Important parameters and basic scale lengths for magnetospheres.

Planet	B_0 (Gauss)	R_p (km)	τ_p (hours)	B_{SW} (nT)	R_{mp} (R_p)	R_{stag} (R_p)
Earth	0.31	6,373	24	$\approx$10	$\approx$10	$\approx$6
Jupiter	4.28	71,398	9.92	$\approx$2	$50 - 100$	$\approx$250
Saturn	0.22	60,330	10.65	$\approx$1	$\approx$19	$\approx$74

Possibly the most striking differences between the magnetosphere of Earth and those of the outer planets is the spatial scale. Earth's radius is an order of magnitude smaller than the radii of Jupiter and Saturn. But spatial scale is relevant only in relation to the dynamics of the system. One critical scale length is established by the distance to the nose of the magnetopause, R_{mp}. This distance can be estimated in terms of solar wind dynamic pressure as discussed by Walker and Russell (1995), or taken from observations (Kivelson and Bagenal, 1999) as in Table I.

However, there is another length scale of importance that arises because plasma motions are controlled through both external and internal stresses. In the absence of external forces and assuming large ionospheric conductivity, currents flowing from

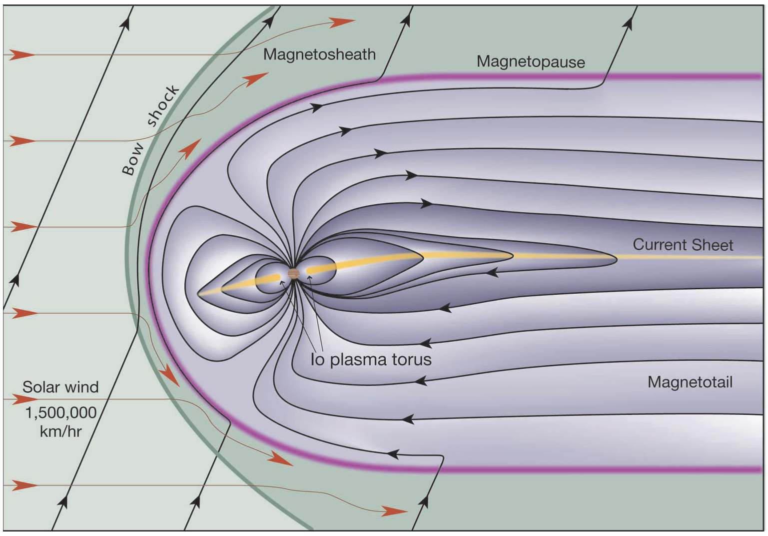


Figure 4. Noon-midnight cut of the Jovian magnetosphere (courtesy of Steve Bartlett and Fran Bagenal, 2004).

the ionosphere to the magnetosphere cause the plasma to rotate at the angular speed of the central planet, a pattern referred to as corotation. Concurrently, flow patterns imposed by magnetic reconnection with the solar wind can result in sunward flows through much of the equatorial magnetosphere (Dungey, 1961). A flow stagnation point can then develop where the rotational flow opposes that imposed by the solar wind. The distance at which this occurs establishes another important length scale for a magnetosphere. That distance (R_{stag}) can be determined (Wolf, 1995) from

$$\begin{aligned} R_{\text{stag}} &= \left(\Omega_{\text{p}} B_0 R_{\text{p}}^3 / E\right)^{1/2} \\ R_{\text{stag}} &\approx \left(\Omega_{\text{p}} B_0 R_{\text{p}}^3 / 0.1 V_{\text{SW}} B_{\text{SW}}\right)^{1/2} \qquad (10) \end{aligned}$$

where Ω_{p} is the angular velocity of the planet, B_0 is the surface magnetic field at the equator of the planet, R_{p} is the planetary radius, and $\mathbf{E}$ is the average cross-magnetosphere electric field. We approximate $\mathbf{E}$ as $0.1\mathbf{V}_{\text{SW}} \times \mathbf{B}_{\text{SW}}$ in terms of the solar wind speed $V_{\text{SW}} \approx 400$ km/s and the magnetic field at the distance of the planet, $\mathbf{B}_{\text{SW}}$.

For Jupiter and Saturn, rotational stresses dominate the effects of the solar wind ($R_{\text{stag}} \gg R_{\text{mp}}$), whereas at Earth, $R_{\text{stag}} < R_{\text{mp}}$ and solar wind control becomes critical. At Jupiter, the effects of rotation are particularly notable in the region referred to as the middle magnetosphere (Smith *et al.*, 1976). In Jupiter's middle magnetosphere the field lines are stretched radially, as contrasted with the relatively dipolar configuration typical of Earth inward of roughly R_{mp} (compare the noon-midnight magnetic structure in Figure 3 with Figure 4).

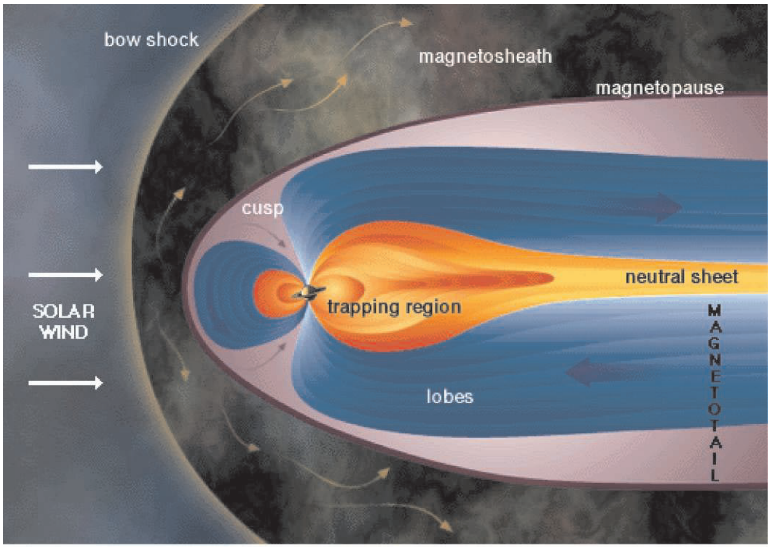


Figure 5. Cut through Saturn's magnetosphere in the noon-midnight meridian (`http://www.windows.ucar.edu/saturn/images/rg.jpg`).

A key to the special properties of Jupiter's magnetospheric field configuration is the heavy ion plasma introduced into the magnetosphere at a rate of 1 ton/s near Io's orbit (at $6R_\mathrm{J}$). Radial stresses imposed by the rapidly rotating magnetospheric plasma greatly distort the underlying dipolar magnetic configuration. A large $\partial B_r/\partial z$ develops and accordingly an azimuthal current $j_\phi \approx \mu_0^{-1}\partial B_r/\partial z$. appears. The azimuthal currents flow in a warped current sheet that is indicated schematically in Figure 4. On the day side, the current sheet extends typically about 2/3 of the distance to the magnetopause (Kivelson and Southwood, 2003).

Beyond the azimuthal current sheet the field lines become the quasi-dipolar field lines of the low density outer magnetosphere. The current disk is ring-like in the sense that it encircles the planet, but unlike Earth's ring current it extends over a large radial range, remains confined close to the equatorial plane, and the current carriers are low energy particles.

Effects of rotation are also present at Saturn and in the inner portion of Earth's magnetosphere but they do not distort the magnetic configuration as they do at Jupiter (see Figure 5). This is because at Earth/Saturn, the plasma density is low and neither the rotational stress nor possible contributions of energy particle pitch angle anisotropy affect **B** significantly.

Returning to Jupiter, we note that rotating plasma with a negative radial gradient of flux tube content may be unstable to the interchange instability; at Jupiter this instability leads to outward radial transport of plasma (Cheng, 1985; Southwood and Kivelson, 1987; 1989). Conservation of angular momentum density ($\rho\omega r^2$ in terms of the density ρ, the angular velocity ω, and the cylindrical radial distance r) implies that outward-moving plasma, initially corotating, will lag corotation

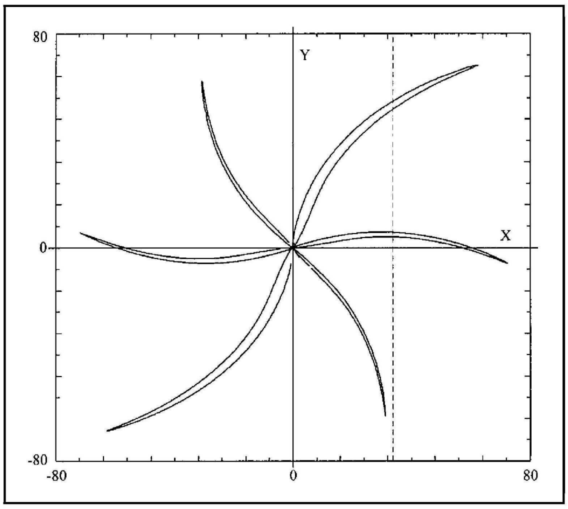


Figure 6. Selected field lines viewed from above (north) in Khurana's (1997) model of Jupiter's middle magnetosphere. Field line bending or "curling" as illustrated here implies radial currents ($\nabla \times \mathbf{B}/\mu_0$) flowing near the equator.

increasingly with radial distance. Because the lag depends on r, which increases along the flux tube from the surface to the equator, the field, "frozen" to the flow, becomes twisted. Figure 6 illustrates this point by showing field lines from a model of the middle magnetosphere viewed from above (Khurana, 1997). The field lines move radially out from the ionosphere and twist or bend back from the radial direction as they approach the equator. As noted, the cause of the bendback is the lag of the plasma relative to corotation as it moves outward. The result is that $\partial B_\phi/\partial r$ is non-zero (especially near the equator) and thus $j_r > 0$ in the near equatorial region. Because the current must be divergenceless, the radial current must close along field lines where they link to the ionosphere as illustrated in Figure 7 from Hill (1979). The radially outward current at the equator can be identified as a corotation-enforcement current because it exerts a $\mathbf{j} \times \mathbf{B}$ force that acts to accelerate the angular speed of the plasma. The closure current at high latitude acts to slow the angular motion of the ionosphere, which can be maintained in corotation through interaction with the collisional atmosphere provided the flux of momentum is sufficient (Vasyliunas, 1994). The current system described, which has no analogue at Earth, has been modeled in detail by K. K. Khurana (1997, and in preparation 2004 with a full magnetopause added). Khurana particularly stresses the role of field-aligned currents that link the equatorial magnetosphere with Jupiter's ionosphere.

Jupiter's ionosphere acts like a TV screen that may light up in some places where currents flow in and out. For example, in Figure 8, an infrared (IR) image of Jupiter, the bright emissions ringing the poles (referred to as the main auroral oval) reveal regions heated by the ionospheric closure of the radial currents that we have

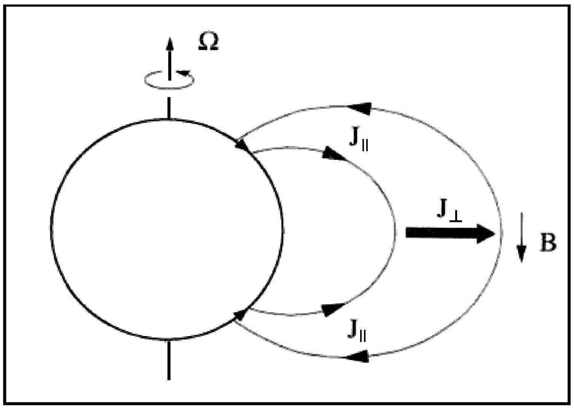
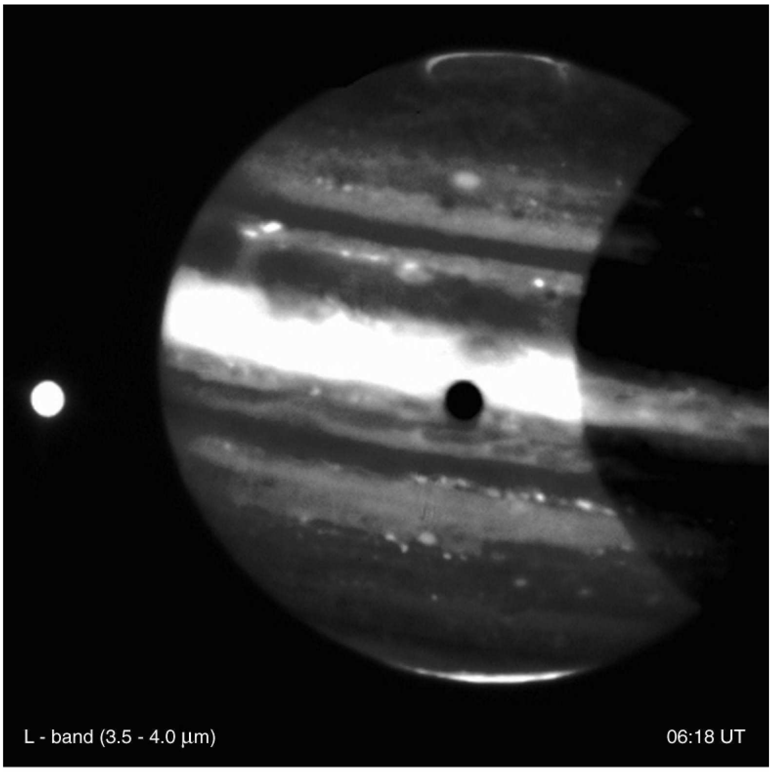


Figure 7. Schematic of currents flowing radially outward in the equatorial plane and closing through the ionosphere (Hill, 1979).



Jupiter and Io (VLT ANTU + ISAAC)

ESO PR Photo 21a/01 (7 June 2001)

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Figure 8. Infrared image of Jupiter (photo from European Southern Observatory).

discussed. The magnetic linkage to the middle magnetosphere is consistent with the flux crossing the middle magnetosphere (Southwood and Kivelson, 2001). In the ionosphere $\mathbf{E} = \eta \mathbf{j}$ where η is the resistivity, which implies that heat ($\mathbf{j} \cdot \mathbf{E} = \eta j^2$) is locally generated in the region of closure currents. Resistive heating produces IR radiation but not emissions in the ultraviolet (UV). IR and UV images need not appear similar. However, Figure 9 shows a high degree of correspondence to the patterns of radiation in the lower frequency bands. Currents are normally carried by the electrons of the low energy plasma whereas UV emissions require excitation by relatively energetic electrons or ions. Hence we are led to ask why energetic charged particles are so closely linked to the ionospheric signatures of currents. For insight, we turn to the signatures associated with currents in the auroral ionosphere at Earth.

In the interpretation of UV aurora at Earth, it has long been accepted that the excitations are driven in regions where upward currents couple the plasma of the magnetotail to the ionosphere. Upward currents require ions to move up from the ionosphere or electrons to move down into the ionosphere. Ionospheric ions are comparatively massive and therefore require large acceleration if they are to move upward as current carriers. Magnetospheric electrons are light and plentiful, but motion towards the ionosphere brings them into an increasingly intense magnetic field and they mirror before they reach the ionosphere. Thus at low altitudes there may not be enough electrons to carry the current. The dilemma of providing current carriers is resolved if an $\mathbf{E}_{\|}$ develops above the ionosphere. With singly charged ions assumed, the field-aligned current density is given by

$$j_{\|} = e n_{\mathrm{e}} \left(v_{\| \mathrm{i}} - v_{\| \mathrm{e}} \right) \approx -e n_{\mathrm{e}} v_{\| \mathrm{e}} \tag{11}$$

where n_{e} is the electron number density and $v_{\| \mathrm{i}}$ and $v_{\| \mathrm{e}}$ the field-aligned ion and electron velocity, respectively. If there are too few electrons to carry the required current density along a portion of a flux tube, Equation (11) tells us that either additional electrons or an increase in the speed with which the available electrons move along the flux tube can compensate. Acceleration by the field-aligned electric field produces the required increase of velocity. Indeed, parallel electric fields are routinely observed in conjunction with auroral arcs. Remarkably, observations by the Fast spacecraft (and earlier polar orbiting s/c) reveal that parallel electric fields are observed not only in the upward current region but may also appear in the downward current region, reflecting the fact that the ionosphere, although a plentiful source of low energy electrons, may need help in providing sufficient numbers of current carriers (Ergun *et al.*, 2000).

The acceleration of current-carrying electrons explains the presence of relatively high energy (10s of keV) electrons in the auroral ionosphere, particularly in the regions where electrons are accelerated downward. The Fast team reports that the structure of field-aligned currents at Earth is often latitude dependent. As illustrated in Figure 10, Alfvénic fluctuations (with both upward and downward currents) are observed at the highest latitude in regions where currents are changing

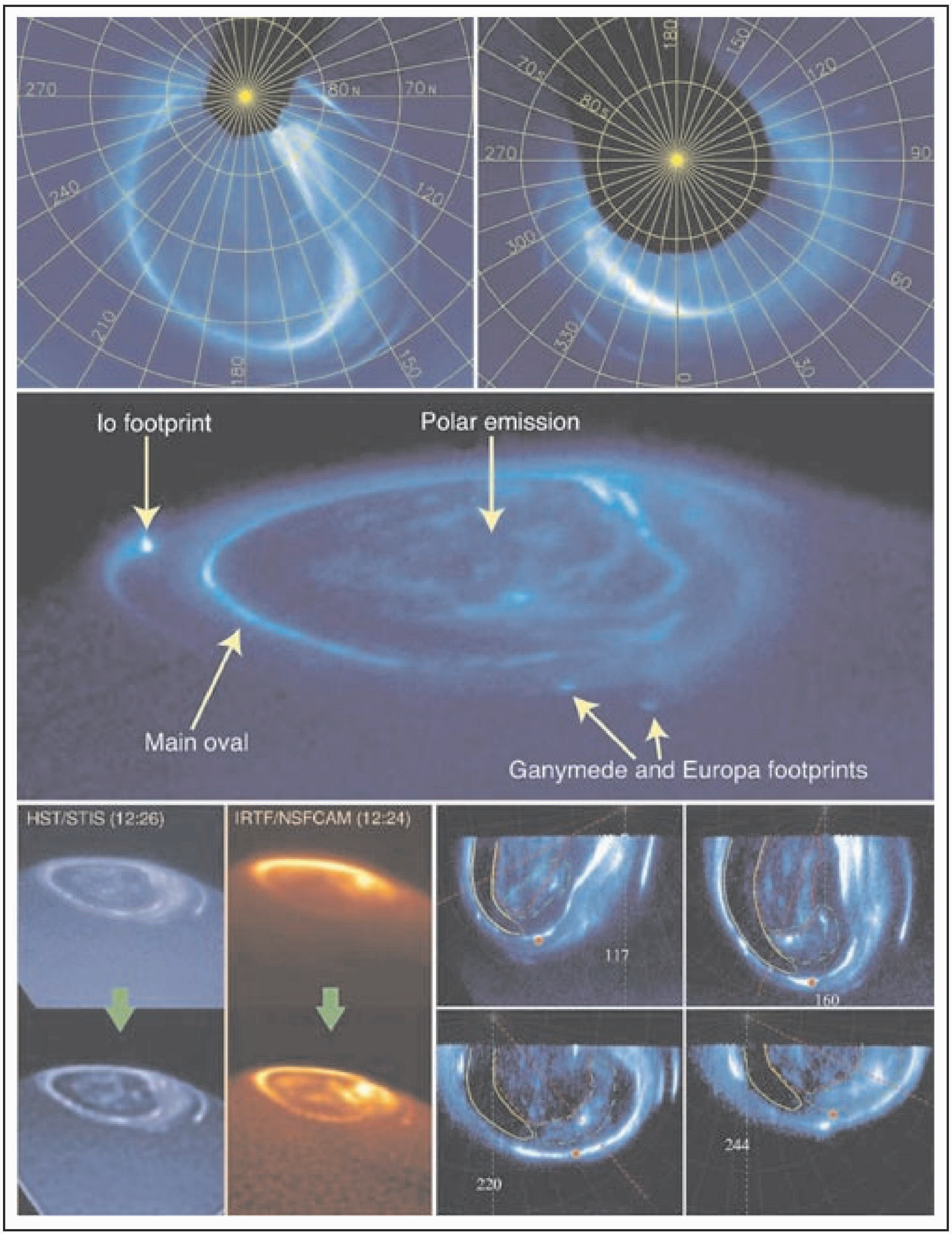

Figure 9. Hubble space telescope images of the auroral atmosphere of Jupiter in UV (blue) and in IR (red). The correspondence of the polar emissions at the two wavelengths supports the view that both types of emission are linked to ionospheric currents.

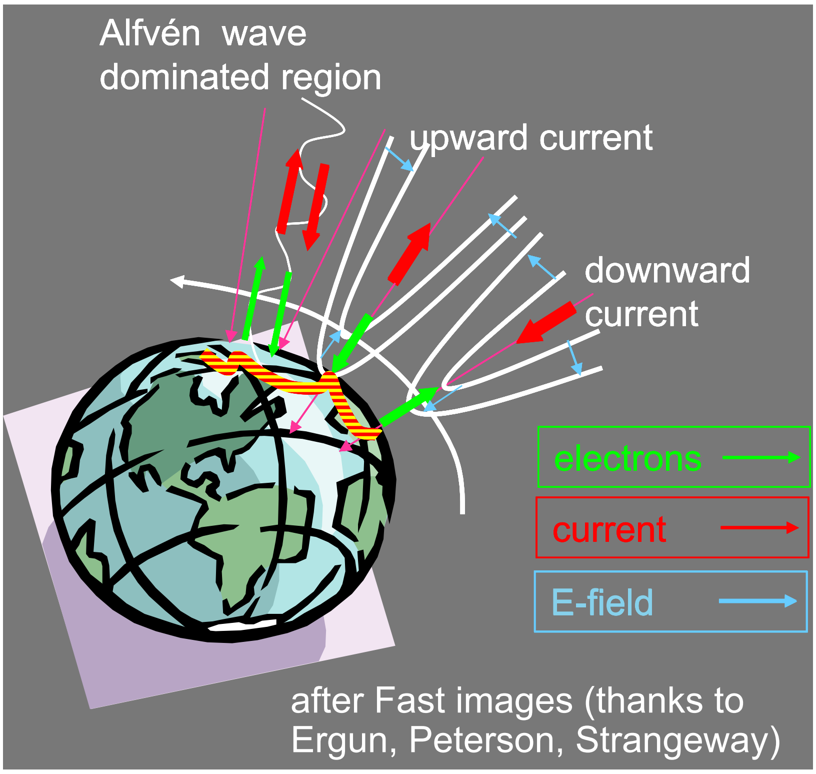

Figure 10. Structure of currents and fields in the auroral region as described in the text. Pink lines represent the magnetic field direction.

in time. At lower latitudes, more stable upward and downward currents appear. The equipotential contours illustrated (white curves) show that the electric fields change direction from being transverse to the magnetic field at high altitudes to being parallel or antiparallel at lower altitudes where the magnetic mirror has excluded a large fraction of the magnetospheric electron population.

The association of parallel electric fields with regions of field-aligned current flow must apply at Jupiter as well as at Earth, even though the processes that cause the currents to flow may differ for the different planets. At Earth, the aurora is linked to magnetotail dynamics. At Jupiter, the main oval is linked to the currents arising from corotation lag. But in both cases field-aligned currents must flow in regions where there is a deficiency of electrons and the problem is solved by imparting acceleration to the available electrons. Estimates by Cowley *et al.* (2004) indicate that at Saturn the plasma lagging corotation drives only weak currents that do not require $\mathbf{E}_{\parallel}$ and do not produce aurora. It is only when acceleration of electrons is required to carry current into the ionosphere that one finds UV aurora in the regions where the heated ionosphere also glows in the infrared.

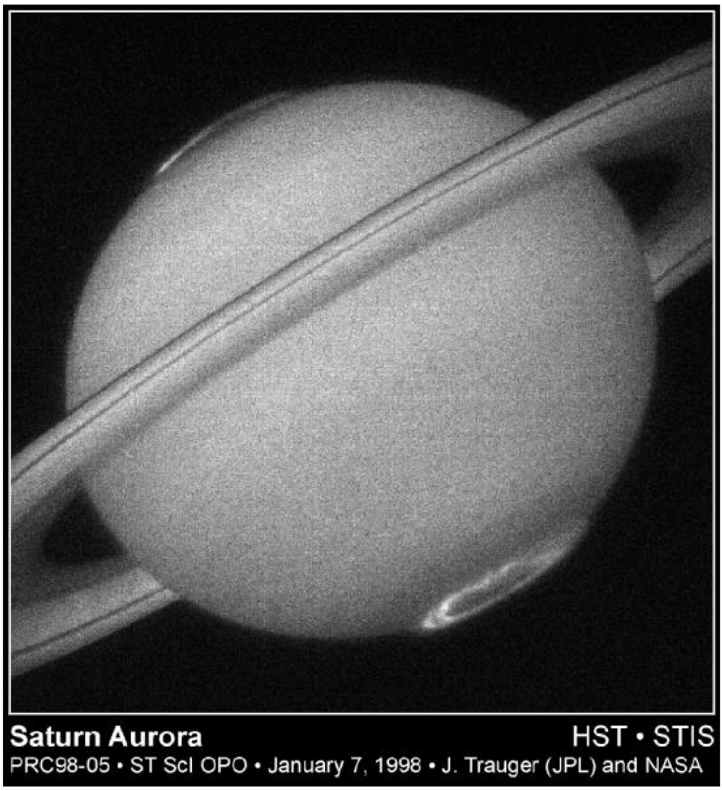

Figure 11. Saturn's aurora imaged in UV by the Hubble Space Telescope.

Field-aligned currents also flow at the boundary between open and closed field lines, both at Earth and Jupiter. These are the currents that drive dayside polar emissions at Earth. Careful examination of the images at the lower left of Figure 9 shows emissions in a ring fully contained within the main oval and these emissions have been identified as the open-closed field line boundary at Jupiter (Pallier and Prangé, 2004). Assuming that the polar oval is the boundary between open and closed field lines, it is reasonable to assume that its intensity will vary as the characteristics of the solar wind, particularly the orientation of its magnetic field, change. Thus it is not unexpected that the intensity of Jupiter's high latitude oval is not constant. In particular, images taken by the Chandra spacecraft revealed impulsive X-ray bursts with variable intensity at a period of 40 minutes (Gladstone *et al.*, 2002), possibly the repetition period of intermittent magnetic reconnection at the dayside magnetopause. At Saturn, Cowley *et al.* (2004) have associated the auroral oval evident in Figure 11 with the open-closed field line boundary, arguing that only at that boundary are the currents sufficiently intense to require parallel electric fields to accelerate electrons. Variable emissions from the auroral oval at Saturn have been reported by Grodent *et al.* (2004) although the link to the interplanetary field

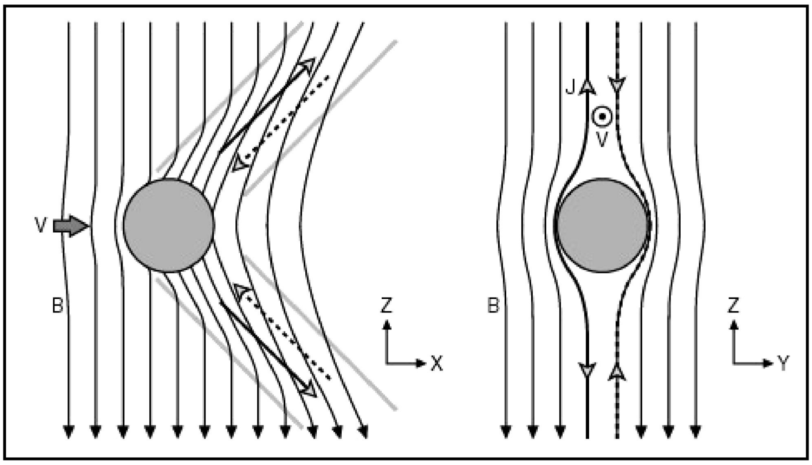

Figure 12. Interaction of a moon with magnetospheric field lines. *Left:* a section containing the field and the flow. *Right:* a section through the field and the radial direction to the planet. The bends of the field and the sense of the field-aligned currents are indicated.

direction has not been established for either Saturn or Jupiter. Some of the variable emissions reported may be linked to substorm-like activity in the magnetotail.

4. Some Current Systems at Jupiter and Saturn Lacking Terrestrial Analogues

A most important feature of the magnetospheres of Jupiter and Saturn that has no terrestrial analogue arises because of the interaction of magnetospheric plasma with the large moons whose orbits lie for the most part within the magnetopause. The Keplerian speed of these moons is lower than the rotational speed of the magnetospheric plasma within which they are embedded, so, in the rest system of a moon, plasma sweeps towards the side that trails its orbital motion. The interaction of the flowing plasma with a moon generates disturbances of various sorts. Of greatest importance for the topic at hand is the bending of field lines linked to the slowing of the plasma by the moon and its atmosphere and by interactions with newly created ions (referred to as pick-up ions) that form a cloud around it (Kivelson *et al.*, 2004). As discussed previously, field bending and currents are linked through Equation (2), thus producing a field and current configuration illustrated in Figure 12. A cross-field current flows radially outward through the moon and/or its ionosphere. Field-aligned currents link the moon and its surroundings to the planetary ionosphere as shown schematically in Figure 13 for some of the Galilean moons of Jupiter. The radial current, analogous to that described in the context of corotation lag, exerts forces to accelerate Io’s motion (quite unsuccessfully) and to slow down Jupiter’s ionosphere to the orbital speed of Io (also not successfully).

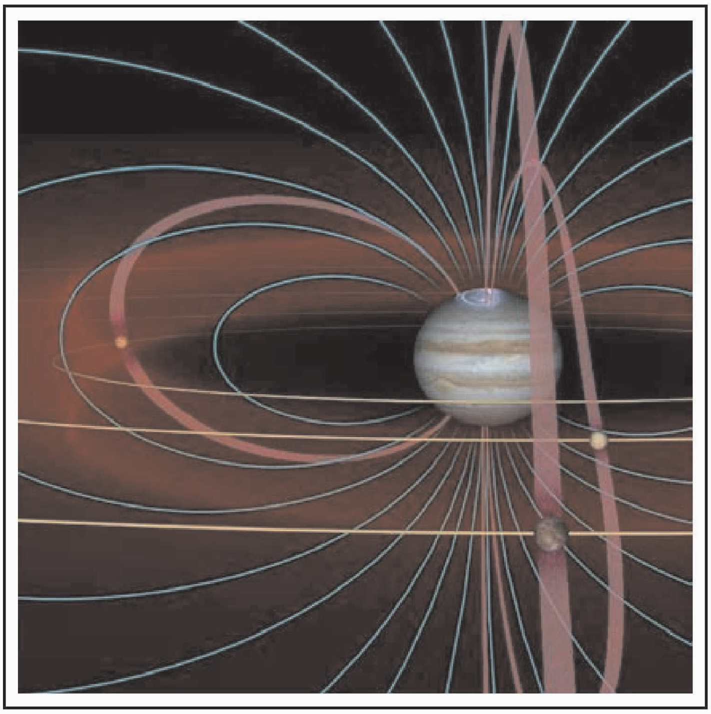

Figure 13. Schematic figure showing currents linking Io (*left*), Ganymede, and Europa (*right*) along field lines to Jupiter's ionosphere.

Like the other current circuits at Jupiter, the currents linking the moons and the ionospheres must flow through regions of low carrier density, regions where the centrifugal stress outward is pushing plasma towards the equatorial point of the field line and regions where the huge gravitational field of Jupiter is pushing plasma towards the ionosphere. This requires that the electrons be accelerated by field-aligned electric fields which accelerate them to energies high enough to produce the UV glow at the feet of the flux tubes of Io, Europa, and Ganymede in Figure 9.

Su *et al.* (2003) take lessons from Earth and apply them to the Io-associated ionospheric signatures (see Figure 14). They attribute the ionospheric emissions at Io's footprint and the trail that leads the footprint in the direction of Io's motion (middle panel of Figure 9) to the effects of $\mathbf{E}_{\parallel}$. The parallel electric field may be implicated in generating Io-controlled decametric radio emissions (Kivelson *et al.*, 2004).

The low altitude electric field in the downward current region can accelerate electrons out of Jupiter's ionosphere, producing highly collimated electron beams that have been observed in passes across Io's wake and its polar cap (Williams and Thorne, 2003). Europa and Ganymede as well as Io link to Jupiter's ionosphere through field-aligned currents. At Saturn, one anticipates evidence of field-

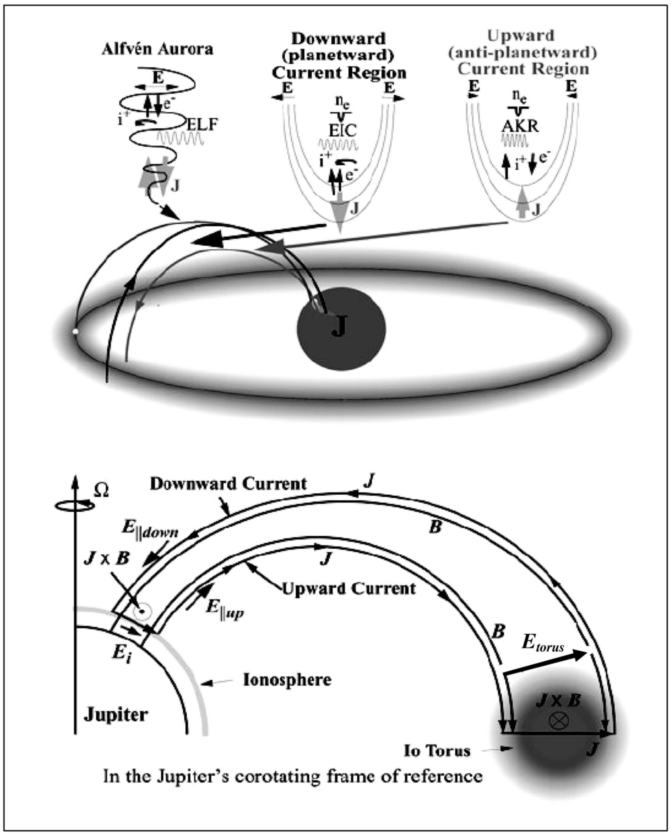

Figure 14. From Su *et al.* (2003) showing the Io-linked currents and proposed structures at low altitude on the flux tubes.

aligned currents and possibly electron beams in the vicinity of the larger moons, particularly at the largest moon, Titan!

An evident feature of the environment of Saturn without parallel at Earth is its ring system. The rings significantly affect Saturn's magnetosphere with strong effects on particle fluxes but details of ring-associated currents remain to be investigated. Rings are present but play a much less significant role in modifying the magnetospheric plasma at Jupiter.

5. The Ring Current – a Terrestrial Current System

In discussing the currents of importance at Jupiter and speculating on currents present in Saturn's magnetosphere, no mention has been made of a ring current. The corotation enforcement currents do flow azimuthally and therefore in a ring around Jupiter, but this current is not an analogue of the terrestrial ring current. At Earth the ring current is important primarily during and following disturbed intervals (storms). The current waxes and wanes in response to solar wind input. It is carried by moderately energetic particles (10s to hundreds of keV ions). The symmetric part of the current is carried by ions trapped on closed drift paths as a result of temporal variations of the convective flow speed. The asymmetric ring current is carried by energetic ions flowing from night to day on open drift paths. There is no clear analogue at Jupiter, probably because effects of the solar wind are less important in a rotation-dominated magnetosphere. At Saturn there is an equatorial current (Giampieri and Dougherty, 2004) probably more like the disk current of Jupiter's middle magnetosphere than like the ring current of the terrestrial magnetosphere. Cassini measurements may reveal if a current-carrying energetic ion population appears at Saturn during disturbed intervals, but this seems unlikely in a rotation-dominated magnetosphere.

6. Summary Remarks

Magnetospheres, like other magnetized plasmas, are coupled over vast spatial domains by currents generated in response to flows and pressure gradients. Particularly dramatic evidence of magnetospheric currents are found in auroral images where the regions coupled to strong upward current flow often are marked by emission of energetic UV photons. At Earth, such strong currents flow principally in response to solar wind-driven geomagnetic activity with some additional signatures marking the open-closed field line boundary. At Jupiter, currents flow into the main oval from a source not present at Earth, the sub-corotating plasma disk. Field aligned currents/electric fields arise naturally wherever currents perpendicular to the background field diverge (for example, at Jupiter near the inner and outer edges of the equatorial plasma disk or in the vicinity of one of the moons). If there are not enough current carrying particles to carry the current, $\mathbf{E}_{\|}$ (along $\mathbf{B}$) develops to speed along the available carriers sufficiently for them to complete the current circuit. The presence of unique current systems such as that arising from corotation lag at Jupiter and that arising from the ring current at Earth are useful as diagnostics of the relative importance of rotational and solar wind influences on the magnetosphere. Saturn is rotationally dominated and in that sense closer to Jupiter than Earth. Despite being rotationally dominated, Saturn's azimuthal currents are comparatively weak, meaning the field is stretched much less than Jupiter's relative to the dipole field, because Saturn lacks a strong source of pick-up ions like Io.

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