A new perspective concerning the influence of the solar wind on the Jovian magnetosphere

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Abstract. The solar wind exerts a strong influence on the Jovian magnetosphere in changing its volume, in energizing plasma, and in stimulating the aurora and a host of other associated effects. However, whereas at Earth the dominant solar terrestrial coupling process is magnetic reconnection, the dominant energy reservoir in Jupiter's magnetospheric plasma, continually present, is the kinetic energy of its rotating plasma disk. This "flywheel" produces effects with no terrestrial analogy, some of which we describe here. The most surprising prediction from the analysis of this paper is that remotely sensed symptoms of Jovian magnetospheric activity are likely to occur in conjunction with solar wind pressure decreases. Compressions of the magnetosphere produced by forward shocks and other solar wind pressure increases will heat the magnetospheric plasma but substantially reduce the ionosphere-magnetosphere current systems. The intensity of dayside aurora and of radio wave emissions associated with increased ionospheric-magnetospheric current systems will tend to anticorrelate with magnetospheric compressions and correlate with expansions. The link to the aurora is based on an argument that the auroral zone maps to the plasma disk of the middle magnetosphere and is thus linked to plasma sheet dynamics. The effect of expansion on the plasma sheet is to increase the parallel pressure, setting up conditions that can produce detached plasma "blobs" and enhance mass loss. The analysis is particularly apposite in light of the opportunities for observing solar wind-Jovian interactions using data from both the Galileo and the Cassini spacecraft during the Cassini flyby of Jupiter in late 2000, ideally supplemented by auroral imaging with ground-based and Hubble telescopes.

1. Introduction

In this brief communication we consider some critical aspects of the effect of the solar wind on the Jovian magnetosphere. We consider whether increases and decreases of the solar wind pressure, as produced, for example, by forward-reverse shock pairs, can trigger the variations in magnetospheric activity reported by space and ground-based monitors. We conclude that such events represent an important element of external control of the Jovian magnetosphere. However, as we show that decreases in pressure have the largest effect, the details of our conclusions may seem counterintuitive to many. Our work parallels arguments presented almost 20 years ago by Nishida and Watanabe [1981] but here revisited in the context of the greater understanding of the Jovian system provided by both spacecraft and ground observations in the intervening years.

In the terrestrial magnetosphere, magnetic reconnection at low latitudes is, to a first approximation, the dominant process through which the solar wind controls the dynamics. Thus the field direction is the most important interplanetary parameter for control of magnetospheric activity at Earth. Although there is every reason to believe that reconnection with the interplanetary magnetic field also occurs at Jupiter (see discussion by Cowley et al. [1996] and Walker et al. [2000]), we propose that it is not likely to have a dominant role as at Earth.

The variability in the Jovian solar wind interaction has been recognized for > 25 years. One of the first magnetospheric properties estimated following the discovery of Jupiter's substantial planetary magnetic moment was the scale of the magnetosphere (see the reviews of Acuna et al. [1983] and Carr et al. [1983]). Neglecting the contribution of internal plasma pressure, the estimated nose distance (distance from Jupiter to the subsolar point of the magnetopause) was ~50 R_J (1 R_J is Jupiter's radius, 71,000 km). Solar wind measurements from the Pioneer 10 and 11 spacecraft revealed that the solar wind dynamic pressure routinely varies by an order of magnitude at Jupiter's distance where corotating interaction regions have developed their full structure [Smith et al., 1978]. It was immediately clear that the magnetosphere was not only big but also likely to experience changes in size quite frequently. Indeed, Pioneer 10 recorded magnetopause crossings in the morning sector at distances that differed by a factor of ~2 during a 3+ day traversal of the outer magnetosphere on the dayside [Intriligator and Wolfe, 1976; Smith et al., 1978], and other spacecraft have reported dayside positions separated by factors of ~1.5 or greater in similar time intervals [Kivelson et al., 1997; Huddleston et al., 1998].

The speed of inward displacement during compressions is not firmly established. Displacements of ~50 R_J have been found to take place in < 4. This requires a displacement velocity larger than the speed of the spacecraft, i.e., ~10 km s^{-1}, throughout the outer portions of the magnetosphere, but this is only a lower limit. More probable is that compression occurs at close to the solar wind speed.

The dominant energy reservoir in the magnetospheric plasma is the kinetic energy of its rotating plasma disk. Furthermore, the plasma of the Jovian magnetosphere is largely produced from a
source deep within the magnetosphere, the Io plasma torus. Heavy ions are injected from the Io vicinity at the rate of \(-1 \text{ t s}^{-1}\). Most of this mass must be transported radially outward through the Jovian system. The physical consequences are described in the classic paper by Hill [1979]. The outward transport of mass means that in steady state there must also be outward transport of angular momentum. Moreover, everywhere one expects some departure from corotation with greater departure at large radial distances [Kane et al., 1999, and references therein].

In Hill's [1979] picture the outward mass transport in the magnetosphere requires that there be a continual supply of angular momentum from the planet. The actual transfer of angular momentum should be done through Alfvén waves. Any departure from isorotation on a flux tube will bend the field out of the meridian so the magnetic tension exerts a torque and excites Alfvén waves. The waves convey momentum between the ionosphere and the equatorial regions. It follows that as long as the Alfvén travel time is greater than a typical radial transport time, part of the lag from corotation will be due to incomplete transfer of angular momentum by the Alfvén waves. Indeed, even if the travel time is less than the radial transport time, it may require multiple bounces of the waves to communicate the torque required to impose partial corotation. Working against the waves' effectiveness are not only potentially bad impedance matching with the ionosphere, but also the low Alfvén speed inside the high-density regions, internal reflections at the edge of the disk/torus, and delays arising from the well-known reduction in Alfvén mode propagation speed (by a factor \(1 - (\beta_p - \beta_A)/2\)) if there is a parallel pressure anisotropy in the disk [Hasegawa, 1975]. Here \(\beta_p = p_{\perp}/(B^2/2\mu_0)\) and \(\beta_A = B^2/(2\mu_0)\) where \(p_{\perp}\) and \(p_{\parallel}\) are the perpendicular and parallel plasma pressure and \(B^2/2\mu_0\) is the pressure of the magnetic field B.

Discussions of the implications of corotation and departures from it in the Jovian magnetosphere have, by and large, concentrated on quasi-steady conditions. The matter investigated by this paper is something specifically time-dependent, the effect that changing solar wind pressure imposes on the rotating magnetosphere.

2. Dynamics of the Jovian System

A schematic of the dayside Jovian magnetosphere is shown in Figure 1 [Smith et al., 1976]. On the basis of measurements from Pioneer 10 and 11, Smith et al. distinguished several regions of the Jovian magnetosphere (inner, middle, and outer) by their magnetic structure as Figure 1 illustrates. Embedded in the middle magnetosphere, deep within the magnetospheric cavity, is a disk of plasma that distends the field at right angles to the Jovian rotation axis. Here the plasma pressure in the disk must be comparable with the surrounding field. The ions of the disk have largely come from the inner magnetosphere, where the field is dipolar. The moon, Io, orbits within this region and is the primary source of material for the Jovian magnetosphere. The last major feature shown by Smith et al. is the region in the outer magnetosphere, near the magnetopause, where the field becomes predominantly southward oriented and the level of fluctuations increases considerably [Kivelson, 1976]. This has been called the "cushion" region by V.M. Vasyliunas. Simple pressure balance ideas suggest that both in the outer and middle magnetosphere, although the field points in very different directions, the field pressure is roughly comparable with the pressure in the plasma disk. This is borne out by observation. The field amplitude outside the current sheet seems to vary slowly with radial distance and is typically between 6 and 12 nT. It is worth noting that disk plasma is confined both by magnetic pressure acting perpendicular to the magnetic field and by centrifugal force acting along the field to confine the thermal plasma to regions near the magnetic equator.

3. Effect of a Shock on the Jovian Magnetosphere

Shocks in the solar wind represent possibly the most important mechanism for changing the size of the Jovian magnetosphere and inducing large inward or outward motions. Not only are shocks more common at Jupiter's distance from the Sun, but also the magnetosphere itself seems very prone to substantial change in response to them.
The effect of the passage of a shock is to increase or decrease the external pressure on the magnetosphere and the magnetosphere will contract or expand accordingly. The response of the magnetosphere to a shock will be fairly nonuniform because the density of the magnetospheric material is concentrated in the plasma disk. As the shock front propagates, the compression will travel rapidly outside the high-density regions of the magnetosphere, but it will slow in the disk itself. Nonetheless, we propose that the compression will be imposed on the disk on a timescale similar to the timescale of the shock's passage past the magnetosphere. The solar wind travels outward from the Sun at a speed of several hundred kilometers per second, typically > 400 km s⁻¹; shocks typically move even faster and thus will traverse the entire dayside magnetosphere (100 R_J) in ~5 hours (half a Jupiter rotation time) or less.

The primary effect of the pressure increase imposed by the shock is to reduce the volume of the magnetosphere and to increase plasma and magnetic field pressure. The compression is likely to be neither uniform nor extremely efficient. Nonetheless, the dayside and regions of weak magnetic field will be the most strongly compressed. To a first approximation, it seems reasonable to regard the electric field induced by the shock as arising from field compression and so purely inductive. If so, no large-scale circulation is induced and, in particular, the field line feet in the ionosphere can be regarded as fixed. Figure 2 illustrates schematically field lines from the plasma sheet in expanded and compressed configurations.

If the volume of the disk material were to be compressed proportionately during the magnetospheric implosion, the shock passage would cause a very large change in the plasma pressure there. An adiabatic compression in all three dimensions by a factor of 2 would yield an increase in plasma pressure of order (2³)⁴/₃ = 2⁵ in the disk. This must be a severe overestimate of what actually occurs, as we now describe.

The shock simply changes the external pressure on the magnetosphere. Within the magnetosphere there must remain an internal balance of forces. The distended field configuration associated with the magnetodisk in the middle magnetosphere requires that the field pressure immediately above and below (see Figure 1) has to be comparable to the gas pressure near the center of the magnetosphere. Within the magnetosphere there must remain an internal balance of forces. The distended field configuration associated with the magnetodisk in the middle magnetosphere requires that the field pressure immediately above and below (see Figure 1) has to be comparable to the gas pressure near the center of the magnetosphere. Within the magnetosphere there must remain an internal balance of forces.
remains unchanged and the compression moves material in the magnetosphere from Lo to L requires its angular velocity to increase as much below the corotation speed of the planet. One concludes that the magnetospheric mass per unit ionospheric flux is any enhanced loss out of the flux tubes. One therefore predicts that the sheet thickening by a factor of just over 2 would be consistent.

If, as a result of the thickening, the plasma were lost from the disk, energy would not be contained in the disk and the assumption of constant entropy in compression would need to be modified. At Earth a major compression would surely be accompanied by considerable precipitation into the ionosphere at the field line feet. At Jupiter, however, even if the bulk of the plasma is undergoing strong pitch angle scattering, one expects the plasma to remain overall well confined to the disk because the plasma is contained in the disk by a centrifugal effect associated with the plasma rotation. The parallel velocity decreases rapidly as a plasma sheet particle travels away from the equator [Bagneal and Sullivan, 1981], and accordingly, the thermal plasma of the torus mirrors near the equator.

4. Effect of Dayside Compression on the Ionosphere

Given the previous considerations, how does rapid compression of the magnetosphere affect the ionosphere? The large compression substantially rearranges the material in the disk, but, as we have noted, there is nothing to suggest that there is any enhanced loss out of the flux tubes. One therefore concludes that the magnetospheric mass per unit ionospheric flux remains unchanged and the compression moves material in the equatorial regions in the disk and torus systematically closer to the planet.

Let us assume that the inward radial displacement of plasma occurs so rapidly that there is no time for torques to be imposed between ionospheric and magnetospheric plasma. Then conservation of the angular momentum of a plasma element that moves from $L_o$ to $L$ requires its angular velocity to increase as $(L_o/L)^3$. Typically, the azimuthal speed in the outer magnetosphere is $< 300$ km s$^{-1}$, much below the corotation speed of 610 (L/50) km s$^{-1}$. Correspondingly, the angular velocity is less than $-0.5\Omega_j (50/L)$ (with $\Omega_j$ the angular velocity of Jupiter). This means that displacement from 100 to 50 $R_j$ will increase the angular velocity from $-0.25 \Omega_j$ to $-\Omega_j$; that is, it will bring the plasma up to full corotation.

Hence one expects compression will reduce the departures from corotation through most of the final compressed magnetosphere, implying that magnetospheric compression will reduce the net torque on the ionosphere. Indeed, reduction of torque on the ionosphere would arise in any displacement for which the final angular velocity satisfies $\Omega_j - \omega_0 > |\omega_0 - \Omega_j|$, where $\omega_0$ and $\omega_f$ are the initial and the final angular velocity, respectively.

The only situation in which the torque would not decrease is the extreme case in which the whole magnetosphere is initially close to corotating. In this case, compression could even bring about a reversal of the torque. However, in such a situation there is an immediate observational consequence. The field in the magnetosphere would adopt a "swept forward" configuration $B_\theta$ in the northern/southern hemisphere antiparallel/parallel to corotation) as the reverse torque is brought in. There are few reports of such configurations in the literature [Hastie and Hill, 1986; Dougherty et al., 1998]. Accordingly, one draws an important overall conclusion, namely, that ionospheric currents and parallel currents associated with the angular momentum transfer required in steady state are reduced strongly by the compression.

There are many epiphenomena associated with field-aligned current flow. Such remotely sensed phenomena as radio emissions, aurorae, and ionospheric Joule heating (and associated infrared emissions) are likely to be directly stimulated by the electrodynamical ionospheric-magnetospheric interaction represented by the field-aligned current system. Indeed, it is our contention that the dominant localized arc structure of the observed aurorae on the dayside of Jupiter map to field lines threading the plasma disk. In an appendix to this paper we explain our basis for this view. Overall, one comes to an unexpected conclusion; a solar wind compression leads to a reduction in most of the symptoms of Jovian activity and that this response should be observable remotely.

5. Magnetospheric Expansion

The processes that we have associated with compression of the plasma of the disk and torus could all, in principle, be reversed in an expansion. Accordingly, one expects that the passage of a reverse shock would result in the magnetopause moving outward owing to the reduction in external pressure. Assuming that the reverse shock reduces the solar wind dynamic pressure to its initial state, the field in the middle and outer magnetosphere outside the plasma disk is likely to decrease by a factor of 4. The plasma in disk and torus would then cool owing to the increase in area subtended transverse to the field. If the overall pressure changes by about a factor 4 while the cross-sectional area increases by a similar amount, the thickness of the sheet will also decrease. In addition, as a result of the outward motion associated with the decrease in solar wind pressure, there would be an increased departure from corotation and thus an increased demand from the magnetosphere for angular momentum. Accordingly, one expects that decreases in solar wind pressure will give rise to increased field-aligned current between ionosphere and magnetosphere and thus, by extension, there would be increased allied infrared, UV radio, and other emissions.

6. Nonreversibility

The compression scenario includes elements that might not operate in a strictly reversible manner. The efficiency with which the pitch angle scattering process can transfer energy from parallel to perpendicular degrees of freedom during the outward expansion might be radically different from what happens in compression. This is particularly so if a plasma instability produces the scattering. During the inward motion the continual pumping of heat into the perpendicular dimensions preferentially accelerates equatorially mirroring particles. Then the electromagnetic ion cyclotron instability, for example, would naturally act to counter the growing anisotropy by scattering particles to smaller pitch angle. The same waves would not be unstable if the anisotropy generated inherently by the motion were opposite, as occurs for outward motion. Thus, if no other naturally occurring instability is set up by parallel anisotropy, the pitch angle scattering that we postulated in the compression may
not be sustained during expansion. The ratio of parallel to perpendicular pressure would then increase, with interesting effects that we describe in a separate section to follow.

Our analysis leads to another interesting prediction. From the start of the expansion, the outward motion of the plasma in disk and torus will place a steadily increasing demand on the ionosphere across the entire dayside to maintain approximate corotation. As outward motion starts, Alfvén waves will be launched immediately from the northern and southern edges of the torus or disk plasma. Whereas it may take tens of minutes to propagate Alfvén waves through the dense plasma in the disk, the signals from the edge of the plasma will reach the Jovian ionosphere in a matter of minutes. Hence ionospheric electrodynamic responses can be expected to begin very rapidly after expansion begins, and the onset of any associated remotely sensed phenomena could also start similarly soon after the arrival of the solar wind rarefaction, but the response would grow in latitudinal range over tens of minutes.

7. Cumulative Effect of Compressions and Expansions

Even if compressions and expansions are effectively reversible processes, the cumulative effect of a series of such events contributes to the outward transport of material. The situation bears some resemblance to a similar apparent paradox in the terrestrial system. The Earth system is driven by a burst of reconnection-driven flow that sets up a circulation throughout the magnetosphere. Material is injected from the outer regions and the tail by an adiabatic compressional motion. However, at the same time, on the dayside, material moves out from the inner regions (ring current/radiation belts) and that which reaches the magnetopause is lost. Despite the losses the flow acts as an injection mechanism only because the net transport of material is inward toward particle sinks near the Earth (atmospheric collisions). At Jupiter the source of material is deep inside the magnetosphere. The net motion of material is outward. A sequence of inward compressions and outward expansions will result in net outward transport of plasma as the dominant losses occur either at the magnetopause or more likely in flow down the tail.

8. Effect of Increased Parallel Anisotropy During Expansion

The actual loss of material through the dayside magnetopause could be accomplished by reconnection opening the planetary field lines to interplanetary space. However, even in the absence of solar wind driven reconnection, increased loading of the disk can ultimately lead to the formation of "blobs" of plasma breaking off at the outer edge of the middle magnetosphere and which then become entrained in the outer cushion region. Such detached plasma blobs produce a diamagnetic response in the magnetic field and were first identified as minima or nulls in data from the Ulysses magnetometer [Southwood et al., 1993, 1995; Leamon et al., 1995; Haynes et al., 1994]. The magnetic field bubbles indicate that the planetary field has broken, and the breaking process itself is evident that there must be strong departures from corotation in the outer magnetosphere. Plasma breaks off when the forces in the magnetic field are incapable of keeping the plasma from moving away from the planet. A fortiori, those same forces are going to be unable to maintain the plasma in rotation.

A sudden outward motion of the outer magnetosphere is likely to initiate such behavior. In particular, detachment could be induced by a solar wind rarefaction as a consequence of the proposed nonreversibility of the compression rarefaction process. We have noted that if there is no significant pitch angle scattering during expansion, the parallel pressure will decline with distance much more slowly than the perpendicular pressure. This will have interesting consequences. Near the equator at a distance $r$ from the spin axis, a balance between the centrifugal force, the plasma pressure $P = (p_\parallel, p_\perp)$, and the field maintains equilibrium. Thus

$$\rho \Omega^2 r = -\nabla \cdot P + j \times B,$$

(4)

where $j$ is the current.

At the equator, one has, on substituting for the pressure tensor term and also rewriting the magnetic force,

$$\rho \Omega^2 r = -\nabla \left( p_\parallel + \frac{B^2}{2\mu_0} \right) - \left( p_\parallel - p_\perp - \frac{B^2}{2\mu_0} \right) \frac{\partial \Phi}{\partial \Phi},$$

(5)

where the term $\partial \Phi/\partial \Phi$ is the curvature of the magnetic field. The curvature term increases near the equator. In the outer magnetosphere it will be the dominant term in the radial component of the force near the equator unless the pressure anisotropy remains such that

$$p_\parallel \approx p_\perp + \frac{B^2}{\mu_0}. \quad (6)$$

One sees that a growth in parallel anisotropy could well increase the radial force at the equator and give rise to an imbalance of forces. The imbalance would change the field configuration, thinning the outer portion of the plasma sheet and enhancing the outward motion.

The process is sometimes described as ballooning. At the outer edge of the disk, the process leads to breakdown of containment of the disk and the introduction of detached blobs of plasma into the outer magnetosphere [Southwood, 1994]. (The ballooning process is described, for example, by McNutt et al. [1987], although we do not accept their proposal that it occurs as close to the planet as Ganymede's orbit.) Further evidence of the condition (6) representing the breakdown of the "elastic limit" of the field [Southwood, 1994] is that Alfvén waves can no longer communicate along $B$ at all, once it is satisfied [Hasegawa, 1975].

9. Previous Work

The ideas presented here, although radical, are not entirely new. The underlying importance of angular momentum transfer is central in Hill's [1979] description of a rotating magnetosphere with mass transport. Moreover, even earlier, Goertz [1978] discussed a process whereby the effect of compressions and rarefactions was not reversible. He was concerned with the behavior of the energetic radiation belt particles rather than the plasma disk particles with which we have been concerned here and he did not recognize the linkage to modified ionospheric-magnetospheric coupling. Nonetheless, his paper repays study.

The work of Nishida and Watanabe [1981] is much closer in spirit to the ideas that we report here. They do recognize quite explicitly that expansions and compressions will have a major effect on the nature of ionospheric-magnetospheric coupling. However, they did not draw the conclusions that we draw here.
The reason is that they assumed that the magnetosphere is kept close to corotation and the coupling time for momentum transfer from the ionosphere to the equator or the reverse is relatively short. Nonetheless, the antecedents of the ideas presented here are to be found in their paper.

10. Conclusions

In the next months the Cassini spacecraft will fly by Jupiter while Galileo is still in orbit about Jupiter, providing unique opportunities to examine solar wind–planetary interactions in a direct way hitherto possible only at Earth. At the same time the availability of ground-based or Hubble imaging of the Jovian aurora and other ionospheric phenomena related to magnetospheric activity also render the Cassini flyby period one of great opportunity.

We have stressed ways in which the Jovian magnetosphere is different enough from Earth's that prejudices based on experience of the terrestrial system must be carefully examined. The most important difference lies in the dominant effects of rotation of the Jupiter system for which there is no real analogue at Earth. Largely because of the presence of rotational stresses, we believe that sudden solar wind compressions and expansions are likely to be far more important in controlling the solar wind–planetary interaction than reconnection between the planetary field and the solar wind. Such disturbances are more common at Jupiter (as disturbances steepen as the move outward in the solar system).

A compression of the magnetosphere combined with a pitch angle scattering process moves mirror points along the field toward the ionosphere and thickens the plasma sheet. Direct precipitation of the thermal plasma into the auroral ionosphere during compression is not anticipated, as the plasma remains well trapped in a torus through the centrifugal force. If, as we believe, the major persistent element of the Jovian aurora on the dayside maps to the plasma sheet, we anticipate that during compressions there will be a reduction in the intensity of phenomena associated with the coupling of the ionosphere-magnetosphere system including visible and UV auroral displays, infrared emissions from the Joule heating of the ionosphere, and radio emissions. During rarefactions these phenomena will be enhanced.

There are reasons to query the reversibility of the processes that we describe. Postulating that pitch angle scattering is more efficient during compressions than expansions, we found a scenario in which compressions and rarefactions drive an irreversible cycle in the Jovian system. In this cycle, plasma is lost from the plasma disk during expansions.

It is interesting to note that there are similarities between the ideas we advance here and a rather similar coupling of radial transport and pitch angle scattering invoked to explain stormtime energetic electron behavior in the magnetosphere [Liu et al., 1999]. A further recent paper with clearly similar underlying ideas is that of Mauk et al. [1999]. They point out that energetic particle injection events could be triggered by solar wind rarefactions. This idea fits very well with our ideas here and embraces an aspect that we have not yet integrated into our picture. Prangé et al. [2001] report correlations between auroral intensifications and disturbed magnetospheric conditions. They note intermittency with typical recurrence every 4 to 10 days. This type of related auroral magnetospheric activity would be consistent with our description, although other sources of disturbances could have the same consequences.

One can note that the cycle of compression and rarefaction is imposed on the plasma sheet also by the natural rotation of the magnetosphere. There can be no doubt that on a smaller scale, the kinds of processes we have discussed being suddenly induced by
a solar wind compression or rarefaction are imposed less impulsively on the confined plasma of the plasma sheet as it rotates from dawn to noon to dusk to night. Some of the known asymmetries of the Jovian system (e.g., dawn auroral storms or the thicker plasma sheet seen in the afternoon) may be explained by adapting our ideas to the steady state. We intend to pursue this further.

Appendix A: Magnetic Mapping of Jovian Auroral Activity

The conclusions of this paper hinge critically on an assumption that current systems generated in the plasma sheet are associated with the maintenance of the aurora. This relationship requires that the field lines from the plasma disk map to the region where the aurora is observed. Mapping is sensitive to uncertainties in the location of the auroral emission and of both the internal field model and the model used to represent the magnetospheric current sheet. This latter contribution is particularly important in the outer magnetosphere.

Properties of the ultraviolet aurora as observed by the Voyager spacecraft are reported by Sandel et al. [1979], Broadfoot et al. [1981], and Herbert et al. [1987]. Earth-orbiting satellite observations include, among others, those of Connerney et al. [1993], Gerard et al. [1994], Waite et al. [1994], Clarke et al. [1996; 1998], Vasavada et al. [1999], and Prangé et al. [2001]. The location of the foot of the Io flux tube as revealed by both IR and UV emissions eliminated the possibility that the aurora mapped to radial distances at or near 10 (i.e., near and beyond 5.9 \( R_j \)) and led to a significant improvement of the internal field model [Connerney et al., 1998]. Later observations of the Ganymede footprint visible equatorward of the auroral oval [Clarke et al., 1998] made it clear that the source of the aurora is outside of 15 \( R_j \) (although the mapping of Vasavada et al. appears to conflict in places with this expectation). Recently, Satoh and Connerney [1999] have further analyzed the auroral mapping, noting that the region inside of 12 \( R_j \) does not correspond to the main oval which they link to the equatorial region between 12 and 30 \( R_h \), though they indicate that the upper bound of the equatorial mapping could be at larger distance than 30 \( R_h \). We believe that the upper limit is indeed uncertain, because at large equatorial distances the model adopted for the current sheet affects the mapping greatly and also because the location of the high-latitude cutoff of the aurora is poorly defined. We suggest that the mapping from the southern hemisphere aurora is particularly useful as plots of surface field strength (Figure A1) given by Acuna et al. [1983], based on the model of Jupiter's magnetic field produced following the Voyager flyby, reveal more longitudinally dependent anomalies in the northern polar region than in the southern polar region.

In Figure A2, we show a plot from Clarke et al. [1998] indicating what is referred to as the reference auroral oval. This is merely an estimate of the typical location of the polar auroras. With the magnetic pole tilted by \(-10^\circ\) toward 200\(^\circ\) in the northern hemisphere or correspondingly 20\(^\circ\) in the southern hemisphere, it is evident from Figure A2b that the southern reference oval lies \(-10^\circ\) from the magnetic pole and is both more compact and more circular than the reference oval in the north. This is consistent with the evidence that the contribution of nondipolar terms is concentrated in the north and suggests that it is more desirable to map field lines to the equator from the southern hemisphere rather than the northern hemisphere.

With the auroral oval at \(-10^\circ\) \(\pm\) 2\(^\circ\) colatitudes relative to the dipole axis, one can map auroral field lines from the Jovian surface to the magnetic equator. In a dipole the colatitude (\(\theta\)) of a field line foot and the \(L\) parameter (in \(R_j\)) of the equatorial crossing point are related by

\[
\sin \theta = L^{-1/2}
\]

Thus 10\(^\circ\) colatitude maps to a radial distance \(L \approx 33\), consistent with the outer limit of the estimate by Satoh and Connerney [1999] from more rigorous mapping arguments.

The uncertainty in the upper limit of the equatorial region that maps to the auroral oval becomes particularly clear if one compares the magnetic flux per 20 \( R_j \) extent of the equatorial current sheet beyond \(L = 30\) with the flux of the conjugate regions near the magnetic pole. The current sheet field (minimum \(B_{eq}\) is roughly the normal component at the current sheet crossing) between 30 and 50 \( R_j \) is of the order of 10 nT, while \(B_{e\,\text{surf}}\), the surface vertical component at high latitude, is of the order of 10 G or 10\(^6\) nT (as evident from Figure A1). Thus
References


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