The Magnetosphere of Jupiter: Coupling the Equator to the Poles

Fran Bagenal
Laboratory for Atmospheric & Space Physics
Astrophysical & Planetary Sciences Department
University of Colorado, Boulder

Abstract

Jupiter is a planet of superlatives: the most massive planet in the solar system, rotates the fastest, has the strongest magnetic field, and has the most massive satellite system of any planet. These unique properties lead to volcanoes 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. There are strong differences between the magnetospheres of Earth and Jupiter but there are also underlying basic physical principles that all magnetospheres share in common. This paper provides a rough sketch of the magnetosphere of Jupiter, briefly describes current understanding and lists outstanding issues. As at Earth, a major issue of the jovian system is how the magnetospheric plasma is coupled to the planet’s ionosphere.

Keywords: Jupiter, magnetosphere, ionosphere-magnetosphere coupling

Introduction to the Magnetosphere of Jupiter

The objectives of this paper are to summarize the basic properties and outstanding issues of the magnetosphere of Jupiter for a readership that is more familiar with the magnetosphere of Earth and to encourage terrestrial magnetosphericists to apply their expertise to less-explored territory. 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 (Kivelson et al. 2004), the particular case of Io (Saur et al. 2004), the plasma torus (Thomas et al. 2004), the magnetospheric configuration (Khurana et al. 2004) and dynamics (Krupp et al. 2004), Jupiter’s aurora (Clarke et al. 2004) and the radiation belts (Bolton et al. 2004). Citations in this article are largely limited to recently published papers.

The strong magnetic field of Jupiter (whose dipole moment and surface field are respectively 20,000 and 14 times stronger than Earth) embedded in a solar wind of ~30 times weaker ram pressure produces a vast magnetosphere with a length scale 100 times that of the Earth (see Figure 1). In fact, most of the terrestrial magnetosphere would fit within the planet Jupiter itself. The opposite polarities of the jovian and terrestrial magnetic moments means one has to watch out for changes in sign when comparing the electrodynamics of the two systems. Unlike the terrestrial magnetosphere whose dynamical behavior is largely controlled by the interaction of the planet’s magnetic field with the interplanetary medium, the magnetosphere of Jupiter is strongly dominated by the rotation of the planet that spins with a 10-hour rotation period. The magnetosphere of Jupiter extends well beyond the orbits of the Galilean satellites – Io, Europa, Ganymede and Callisto – and it is these satellites that provide some of the interesting
magnetospheric phenomena. In particular, Io loses ~1 ton per second of atmospheric material (mostly SO$_2$ and dissociation products) that, 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 just outside the orbit of Io. Radial transport of the iogenic plasma occurs through a process of fluxtube interchange whereby magnetic fluxtubes that are relatively full of plasma move outwards and relatively empty fluxtubes move inwards. The timescale for this process of radial transport is on the order of 20-80 days, equivalent to 50-400 jovian rotations. The radial motion is thought to be slowest near Io’s orbit and speeds up farther out. Plasma from the Io torus extends out from Jupiter as an equatorial plasma sheet throughout the magnetosphere. The coupling of this equatorial plasma to the jovian flywheel is the main topic of this paper.

*Response to compression* – An important consequence of a strong internal plasma source and an equatorial plasma sheet is that the magnetosphere of Jupiter is much more compressible than that of Earth. Simple pressure balance between the ram pressure of the solar wind and the magnetic pressure of a dipole produces a weak variation of the terrestrial dayside magnetopause distance ($R_{mp}$) with solar wind density ($\rho$) and speed (V): $R_{mp} \sim (\rho V^2)^{1/6}$. Measurements of the magnetopause locations at Jupiter indicate a much stronger variation with $R_{mp} \sim (\rho V^2)^{1/3}$. Consequently, a factor of 10 variation in ram pressure at Earth changes the magnetopause distance by only 70% while at Jupiter the x10 variations in solar wind pressure often observed at 5 AU cause the dayside magnetopause to move between ~100 and ~50 Rj (where 11 Re ~1 Rj=71,400 km). This greater compressibility of the jovian magnetosphere is due to a significant contribution of the plasma pressure in the equatorial plasma sheet as well as a substantial system of azimuthal currents that weaken the radial gradient of the magnetic field compared to a dipole.

*Io plasma source and torus* – The physical phenomena associated with the interaction of magnetospheric plasma with the satellite Io is a whole topic on its own (e.g. Kivelson et al. 2004, Saur et al. 2004, Schneider & Bagenal 2006). Here we summarize the salient facts to provide context for the central topic of ionosphere-magnetosphere coupling. Figure 2 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 encircling most of the way around Jupiter. Io loses about 1-3 tons of neutral atoms per second. How much of the neutral escape is in molecular form (SO$_2$, SO or S$_2$) vs. atomic O or S is not known.

Compared with the local plasma that 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 (see Figure 2b). 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 1/3 to 1/2 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 does not add
more plasma to the system.

Most of the ionization and charge exchange processes occur in the extended neutral clouds and add only ~2% of the torus density per jovian rotation. Thus, the electrical currents associated with the pick-up process are weak and the coupling to the jovian ionosphere sufficient to keep the torus plasma close to corotation. However, between 20-50% of these pick-up processes occur close to Io in a narrow boundary layer upstream and on the flanks of Io. The currents flowing through Io’s ionosphere/pick-up region close along field-aligned currents towards Io on the jovian flank (“upward current” relative to Jupiter) and away from Io on the anti-jovian flank (“downward current” relative to Jupiter). How these parallel currents close at high latitudes – whether in the plasma as Alfvén waves, through Jupiter’s ionosphere or via potential structures – is a major topic of research and is thought to be related to the auroral emissions associated with Io at UV, IR and radio wavelengths as discussed below.

The Io plasma torus (Figure 3) has total mass of ~ 2 Mton which would be replenished by a source of ~1 ton/s in ~23 days. Multiplying by a typical energy (T_i~60 eV, T_e~5 eV) we obtain ~6 x 10^{17} J for the total thermal energy of the torus. The observed UV power is about 1.5 TW emitted via >50 ion spectral lines, most in the EUV. This emission would drain all the energy of the torus electrons in ~7 hours. Ion pick-up replenishes energy (and Coulomb collisions feed the energy to the 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 a source of hot electrons (Barbosa 1994; Delamere and Bagenal, 2002)

Voyager, Galileo and, particularly, Cassini observations of UV emissions from the torus show temporal variability of torus properties (e.g. Steffl et al. 2004; Delamere et al. 2004). Models of the physical chemistry of the torus match the observed properties with a production of neutral O and S atoms, a radial transport time and a source of hot electrons (Delamere & Bagenal 2002; Delamere et al. 2004). The Voyager 2 observations (1979) suggest higher neutral production rate (2.6 ton/s), rapid transport (23 days) and a high O/S ratio (4). By contrast, the Cassini (2000) data indicate the lowest production rate (0.6 ton/s), slow radial transport (50 days) and a low O/S ratio (1.7). The variation in torus emissions observed over several months by Cassini suggest changes in the output of Io’s volcanic plumes (Delamere et al. 2004).

Plasma composition – Before moving on to the main topic of magnetospheric dynamics it is worth noting some clues provided by plasma composition (e.g., Geiss et al., 1992; Khurana et al., 2004; Mauk et al., 2004). Figure 4 nicely illustrates the elemental and charge state composition of (suprathermal) ions at Earth, Jupiter and Saturn measured by the same instrument. The three panels show data (at ~100 keV) taken by the Charge Energy Mass Spectrometer (CHEMS) when Cassini flew by Earth and Jupiter and then entered orbit about Saturn (Hamilton et al. 2005). At Earth the solar wind (protons, alpha particles, and high charge state heavy ions) and Earth’s ionosphere (singly charged oxygen and nitrogen) are strong plasma sources. At Jupiter the source is the volcanoes of Io (low charge state oxygen and sulfur ions from dissociation of sulfur dioxide). At Saturn plasma sources include the rings, the surfaces of the icy moons and, probably most importantly, the recently discovered volcanic plumes on Enceladus (singly charged oxygen, OH and water ions). The lower number of counts measured at Jupiter reflects the short duration and distant approach of the Cassini flyby. The obvious initial observation is that satellite sources dominate the magnetospheres of the outer planets while solar wind and ionospheric sources are important for Earth. Nevertheless the presence of He^+ ions indicates that ionospheric material does escape the giant planets. Early theoretical estimates suggested the ionospheric flux of protons could be ~10^{28} s^{-1}, comparable to the
flux heavy ions from Io (Thorne 1981; Nagy et al., 1986). An optimist would be encouraged by the thought that further investigation of the ionospheric source may provide clues about magnetosphere-ionosphere coupling. A realist might point to the fact that all three types of current systems – upward, downward and Alfvénic – are known to cause ions to escape the terrestrial ionosphere into the magnetosphere. In either case, this promises to be a fruitful area for comparison between Earth and Jupiter.

Plasma transport – The earliest theoretical studies concluded that the magnetosphere of Jupiter is “all plasmasphere” with little influence of solar-wind-driven convection. Indeed, rotation dominates the plasma flows observed in the magnetosphere out to distances of ~100Rj (Frank & Paterson 2002; Krupp et al. 2001, Krupp et al., 2004). Yet we see iogenic plasma throughout the vast magnetosphere. Plasma transport away from Io’s location implies the plasma moves either inwards or outwards across magnetic L-shells. As reviewed by Thomas et al. (2004), Jupiter’s magnetosphere is a giant centrifuge with radial transport outward being strongly favored over inward transport. The fluxtube interchange instability is analogous to the Rayleigh-Taylor instability of fluid dynamics and entails fluxtubes laden with denser, cooler, iogenic plasma moving outwards and relatively empty fluxtubes containing hotter plasma from the outer magnetosphere moving inwards. The 20-80 day timescale for replacement of the torus indicates surprisingly slow radial transport that maintains a relatively strong radial density gradient. Numerical modeling with the Rice Convection Model – Jupiter suggests radial shear in the azimuthal flow (i.e. increasing lag behind corotation with distance) stabilizes the interchange motion and drives the characteristic size of interchanging fluxtubes to small-scales (Pontius et al. 1998; Goldstein et al. 2001). While the flow direction remains primarily rotational, both the lag behind corotation and local time asymmetries increase steadily with distance from Jupiter. In the midnight-dawn sector bursts of flow down the magnetotail are observed while on the dawn flanks occasional strong bursts of super-rotation are observed. Below we return to these deviations from corotation and discuss how they relate to auroral structures.

Field structure – As the equatorial plasma rapidly rotates it exerts a radial (centrifugal) stress on the flux tubes. Additional stress is provided by the radial pressure gradient of hot plasma, inflating the magnetic field. The net result is a stretching of the initially dipole field lines away from Jupiter, in a configuration that implies an azimuthal current in the near-equatorial disk (see Figure 5). The righthand side of Figure 5 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. Alternatively one can think of sub-corotating plasma pulling back the magnetic field away from radial. Out to about 50 Rj the field is pretty azimuthally symmetric but Figure 5 shows strong local time asymmetries develop in the outer magnetosphere (Khurana 2001; Khurana & Schwarz 2005).

Figure 6 compares the current systems in the magnetospheres of Earth and Jupiter (Khurana 2001). In addition to the azimuthal and radial currents mentioned above, there are field-aligned parallel currents (similar to the terrestrial Region 1 and 2 currents), magnetopause and magnetotail currents. While these two magnetospheres are driven by very different processes, the current systems are similar, albeit the net current magnitudes are much greater at Jupiter. Note that the opposite directions of the planetary dipoles results in currents of opposite directions.

Three Types of Aurora

Just as at Earth, the jovian auroral emissions are important indicators of magnetospheric processes. With limited spacecraft coverage of the jovian magnetosphere, auroral activity
is a projection of magnetospheric processes (communicated via precipitating energetic particles) onto the atmosphere and thus allows us to study global processes not yet accessed by spacecraft. Figure 7 illustrates the three main types of aurora at Jupiter (see reviews by Bhardwaj and Gladstone 2000; Clarke et al. 2004). There is a fairly steady main auroral oval that produces $\sim 10^{14}$ W globally and can exceed 1 W m$^{-2}$ locally. This oval is quite narrow corresponding to $\sim 1^\circ$ latitude or a few hundred kilometers horizontally in the atmosphere of Jupiter, mapping along magnetic field lines to 20-30 RJ at the equator in the magnetosphere, well inside the magnetopause. Auroral emissions are also observed at the feet of fluxtubes of Io, Europa and Ganymede. While the magnetosphere interaction with Callisto is thought to be much weaker than 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 the way around Jupiter. The third type of jovian aurora is the highly variable polar aurora that occurs at higher latitudes than the main aurora (corresponding to farther magnetospheric distances). We discuss these three types of aurora in turn below.

Main aurora – The fact that the shape of the main auroral oval is constant and fixed in magnetic co-ordinates (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 of open/closed field lines of the polar cap (thought to be only $<10^\circ$ at Jupiter) and maps to well within the magnetosphere. It is difficult to accurately map magnetic field lines because of the strong equatorial currents that 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 fully spin up its magnetosphere.

The top of Figure 8 shows the simple current system proposed by Hill (1979). As the iogenic plasma moves outwards, 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 Pedersen 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/transport from Io and the (poorly-determined) ionospheric conductivity. Matching his simple model to the new Voyager observations (McNutt et al. 1979), Hill (1980) found he could model the observed profiles of azimuthal flow with a source of 2-5 ton/s and an ionospheric conductivity of 0.1 mho. Cowley et al. (2002, 2003) extended the Hill model to include an empirically-derived, non-dipolar magnetic field (see the lower portion of Figure 8). In an attempt to model the narrowness of the observed auroral oval, Nichols & Cowley (2004) added a non-linear ionospheric conductivity that depends on the parallel current, arguing that the Knight relation (assumed to be in the linear regime) would produce a greater energy flux of precipitating electrons as more current is driven by the sub-corotating magnetospheric plasma. This is an active area of research and terrestrial magnetosphericists are encouraged to apply their detailed experience at Earth to the jovian system.

Stepping back from specific models, one asks the basic question of where is the clutch slipping between the jovian flywheel and the load applied by the production and transport of iogenic plasma in the magnetosphere?
A - Between deep and upper layers of the atmosphere? Huang & Hill (1989) argue that the few percent lag behind corotation in the Io torus is due to the local mass-loading driving currents that load the ionosphere and while they say there is sufficient ionospheric conductivity to carry the necessary currents, the coupling of the deep atmosphere to the upper atmosphere (at the ionosphere level) is not sufficient to keep the upper atmosphere corotating. This effect is probably significant for the local mass-loading around Io’s orbit but its importance for the spatially extended loads applied by the equatorial plasma sheet is less clear and a topic for investigation with models of the coupled ionosphere-thermosphere system (see review of Jupiter’s upper atmosphere by Yelle and Miller 2004).

B - Between the upper atmosphere and ionosphere? The coupling between a corotating upper atmosphere and ionosphere is described by the Pedersen conductivity, integrated vertically through the ionosphere. Values of the Pedersen conductivity depend on the vertical profiles of neutrals and electrons which have been deduced for low latitudes from radio occultations but have not been measured at auroral latitudes and may be strongly modified by the precipitating electrons. Strobel & Atreya (1983) quote values of 0.2 mho to be typical for the Pedersen conductivity with values as high as 10 mho where heavily bombarded by energetic auroral electrons (see also Yelle and Miller 2004). While early models were encouraging, more detailed analysis is showing that it is hard to produce the sharp auroral oval and corresponding drop behind corotation unless the iogenic source is particularly large and/or the ionospheric conductivity lower than thought to be typical. If there is significant slippage between the upper and lower neutral atmospheres (as in A above) then less conductivity is needed (Huang and Hill 1989). Increases in the ionospheric conductivity due to electron bombardment increase the momentum transfer from the planet to the magnetosphere rather than producing the decoupling associated with the auroral region.

C – Between the ionosphere and the magnetosphere? Lessons from spacecraft flying through polar regions in the Earth’s magnetosphere suggest that when there is insufficient density of current-carriers, potential drops develop along the magnetic field in narrow regions of strong electric fields which accelerate electrons to sufficient speeds to carry the necessary current. The rotation-driven confinement of plasma to the jovian equatorial region may not provide sufficient density of electrons at high latitudes to carry the necessary parallel currents so one might expect there to be “impedance regions” or potential structures at high latitudes (Mauk et al. 2002). Some argue that such potential structures effectively decouple the magnetosphere from the ionosphere. Others argue that these potential drops are small compared with the cross-field potential across the jovian magnetosphere so that field-aligned potentials play a limited role in any decoupling (Cowley et al. 2003a).

While the main auroral emissions at Jupiter are agreed to be the signature of upward currents (carried by downward-directed electron beams) associated with the lack of coupling of the equatorial plasma to the jovian flywheel, several key issues remain outstanding:

- Are there outward ion beams associated with these upward currents?
- Where along the fluxtube connecting the magnetosphere to the planet does the decoupling occur?
- Can the very narrow width of the auroral oval be modeled with realistic ionospheric conductivities and realistic mass-loading rates?
- Are high-latitude potential structures needed to explain the very narrow width of the auroral oval? What role do they play in de-coupling of the magnetosphere?
from the ionosphere?

- Where do the downward currents (needed to complete the circuit) flow? Are there associated super-thermal electron beams and ion (conic) outflows associated with such downward currents, as found at Earth?

**Io Aurora** – The Io-related aurora are much less powerful than the main aurora. But they have attracted considerable attention partly because of the association with bursts of Io-controlled radio emissions that have been observed for over 40 years but also in the hope they will provide clues about the complex interaction of Io with the surrounding plasma (see reviews by Saur et al. 2004 and Clarke et al. 2004). Voyager 1 measured currents generated in the Io-plasma interaction propagating along the magnetic field towards and away from Io, as shown schematically in Figure 2. The auroral emissions spanning the spectrum from UV to radio wavelengths observed coming from the atmosphere of Jupiter (or close above) indicate that at least some of the energy of the Io interaction and beams of current-carrying electrons must reach the planet.

Early explanations if the Io interaction invoked a direct current loop that flowed through Io and closed in the ionosphere of Jupiter. Voyager observations of a massive plasma torus implied sufficiently slow transmission of Alfven waves that the current might not be in a single closed loop but be carried downstream of Io in a standing pattern of Alfven waves bouncing between north and south ionospheres.

Galileo observations of stagnated flow close downstream of Io have revived the possibility of an Alfvenic disturbance having time to return to Io and directly close the current loop within the ionosphere/pick-up region of Io. In any case, even if the main induction current is carried in a closed current loop, it is clear that large amplitude Alfven waves are generated in the plasma flowing past the interaction region (e.g., Saur et al. 2004; Delamere et al. 2003) which become filamented into high-frequency/small-scale structures as they propagate away from Io (Chust et al. 2005).

Figure 9 presents a sketch of mechanisms, based on experience at Earth’s magnetosphere, that Ergun et al. (2006) propose to explain the Io aurora. The Io-associated aurora are broken down into three sub-regions: (i) the Alfven aurora associated with Io spot; (ii) the upward current region on the Jupiterward side of the wake; (iii) the downward current region on the side of wake away from Jupiter. Ergun et al. (2006) and Su et al. (2006) argue that the Io-spot/Alfven-aurora are associated with an Alfven resonator that is excited in Jupiter’s ionosphere and is responsible for the short S-bursts of radio emission. Delamere et al. (2003) argue that there is a region of about 5-10 Io radii in the wake where momentum of the surrounding torus is transferred (via Alfven waves) to the newly ionized material. In simultaneous studies, Hill and Vasyliunas (2002) and Delamere et al. (2003) both proposed that in the long wake observed to stretch around the planet momentum is slowly added from Jupiter to bring the small “slug” of plasma from Io’s ionosphere (see Figure 2) up to full corotation. Su et al. (2003) argue that the torus plasma is partly decoupled from the ionosphere by a potential drop along the field line. They model this distant wake structure as a steady-state upward current region where a cavity with a ~30 kilovolt potential drop accelerates electrons so that they can carry the current in the low density region between the torus and the ionosphere. Su et al. (2003) argue that the horseshoe or shell electron velocity distribution that is obtained in the cavity region is responsible for triggering the long-duration L-bursts of decametric (DAM) radio emission.

After four decades of studying the Io-plasma interaction and multiple types of associated auroral emissions several key issues remain outstanding:

- Is there a direct current loop between Io and Jupiter’s ionosphere and how much

7
current does it carry?
• How much energy is generated as Alfvén waves by the Io interaction and how much of this energy escapes the plasma torus to high latitudes?
• How much of the Alfvén wave energy that reaches Jupiter’s ionosphere is absorbed vs. reflected?
• What is the nature of the ionospheric Alfvén resonator? Is it responsible for the S-burst radio emission?
• What is the relationship between the Io wake aurora and processes in the torus?

Polar Aurora – The auroral emissions poleward of the main auroral oval (see Figure 10) are highly variable, modulated by the solar wind, and controlled in local time, being usually dark on the dawn side and brighter on the dusk side (see reviews by Grodent et al. 2003; Clarke et al. 2004). The region of magnetic field lines that are open to the solar wind in the polar cap is thought to be very small (~10° half-width). Thus, most of the 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 ejection of plasmoids down the magnetotail (Grodent et al. 2004). Spectral observations of auroral x-ray flares suggest that energetic ions are bombarding the polar atmosphere and may be the signature of the plasmasheet return (downward) current (Waite et al. 1994) or accelerated solar wind ions (Gladstone et al. 2002).

Studies of the highly variable polar aurora are associated with the poorly-understood farther reaches of the magnetosphere and even basic issues remain unknown:
• Where do the regions of polar emissions map to in the outer magnetosphere?
• Where is the polar cap boundary?
• How much of the auroral variability is due to solar wind vs. internal dynamics?

Global Dynamics of The Outer Magnetosphere

A major value of studying the aurora is to explore how these various emissions are related to the dynamics of the outer magnetosphere (see Kivelson & Southwood 2006 and reviews by Khurana et al. 2004; Krupp et al. 2004). Figure 10 combines a summary image of the main auroral features with polar, equatorial and side views of the outer magnetosphere to illustrate the three main dynamical regions.

The innermost region (blue), which we will call the Hill region, comprises the equatorial plasma disk where rotation dominates the flow. At a distance of about 20 Rj 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 region (pink) is the compressible "cushion" or Vasyliunas region (named after his seminal chapter (Vasyliunas 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. On the dusk side the plasma expands outwards (dark pink arrow) and strong currents try to keep the magnetospheric plasma corotating. These strong currents produce the active dusk polar aurora. Kivelson & Southwood (2006) argue that the rapid expansion of fluxtubes in the afternoon/dusk sector means that the second adiabatic invariant is not conserved which results in heating and thickening of the plasmasheet. As the plasma rotates around onto the night side 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 Alfven 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. Kivelson & Southwood (2006) point out that the stretched, equatorial magnetic field becomes so weak that the gyro-radii of the heavy ions becomes comparable to 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 swang around to the dayside. This is in contrast to the concept of a “planetary wind” (Hill et al. 1974; Vasyliunas 1983) where a super-Alfvenic plasma wind blows the magnetic field open and carries flux down the tail (analogous to the solar wind).

The volume of the magnetosphere that is open to the solar wind (green in Figure 10) is completely unknown. Cowley et al. (2003) postulated that there is also a Dungey cycle (similar to Earth) driven by dayside reconnection that carries flux over the poles. Cowley argues that the return flow (following tail reconnection) follows around to dayside, following the dawn magnetopause. There is no evidence as yet of such a solar wind induced convection pattern, nor do we know how much of the polar flux is open to the solar wind.

**Tail Disruption Events**

Pursuing evidence for Vasyliunas’ argument that plasmoids are ejected down the tail, Grodent et al. (2004) found evidence of spots of auroral emission poleward of the main aurora connected to the nightside magnetosphere that flash 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. (2004) estimated that they are coupled to a region of the magnetotail that was about 5 to 50 Rj across and located greater than 100 Rj down the tail. Studies of in situ measurements by Russell et al. (2000) and Woch et al. (2002) lead to conclusions that plasmoids on the order of ~25 Rj in scale were being ejected every 4 hours to 3 days, with a predominance for the post-midnight sector and distances of 70-120 Rj. Could such plasmoids account for most of the plasma loss down the magnetotail? If one approximates a plasmoid to be a disk of 2Rj-thick plasma sheet that has a diameter of 25 Rj and a density of 0.01 cm$^{-3}$, then each plasmoid has a mass of about 500 tons. Ejecting one such plasmoid per day is equivalent to losing 0.006 ton/s. Increasing the frequency to once per hour raises the loss rate to 0.15 ton/s. Thus, even with optimistic numbers the loss of plasma from the magnetosphere due to such plasmoid ejections cannot match the canonical plasma production rate of 0.5 ton per second. On the other hand, a steady flow of plasma of density 0.01 cm$^{-3}$ in a conduit that is 2Rj thick by 300 Rj wide moving at a speed of 200 km/s would provide a loss of 0.5 ton/s. Such numbers suggest such a quasi-steady loss rate is feasible. The question of the mechanism remains unanswered. Three options are 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 planetary wind.

Luck would have it that few of the 33 orbits of Galileo brought the spacecraft to the dusk-midnight sector where these different mechanisms could be tested. The New Horizons spacecraft will fly down the jovian magnetotail as it gains a gravitational boost on its way to Pluto. Data from the particle detectors may allow us to distinguish between these models.

**Mass Budget**

Figure 11 summarizes an approximate mass budget of the magnetosphere of Jupiter. The source of neutrals from Io is on the order of 1-3 ton/s of SO$_2$ and dissociation products. A
range of ½ (Cassini outbound era) to 2/3 (Voyager era) of the Io neutral source suffers charge exchange reactions producing fast neutrals. The rest of the neutral from Io are ionized (1/3 to ½), trapped by the magnetic field and rotate around the planet at approximately Jupiter’s 10-hour spin rate. The 200-900 kg/s of Iogenic plasma fills the magnetosphere of Jupiter. Above we argue that the loss down the magnetotail via major plasmoid events (which produce bursts of aurora) is at most 150 kg/s. The remainder of the magnetospheric plasma must be lost at a steadier rate, probably down the magnetotail, by a process yet to be determined.

**Outstanding Questions**

Major progress has been made in our understanding of the magnetosphere of Jupiter from the Voyager, Ulysses and Cassini flybys as well as 33 orbits of the Galileo spacecraft and observations of the aurora and radio emissions from the Earth. Nevertheless there remain several major outstanding questions:

- What happens above the equator? Spacecraft measurements have been largely limited to the equatorial region. To understand how the magnetospheric plasma is coupled to the poles it is critical to explore the polar regions.
- How is angular momentum transferred from Jupiter to the magnetosphere? Does the slippage behind corotation occur in Jupiter’s atmosphere, the ionosphere or in impedance regions above the ionosphere?
- What happens in the magnetotail? Are plasma losses via steady planetary wind, a small-scale cross-field diffusive “drizzle” or reconnection-driven plasmoid events? Is there a solar wind induced convection pattern similar to that at Earth?
- What triggers disruptions of the magnetosphere and auroral flares?
- What are the roles of Io’s volcanism vs. solar wind in magnetospheric variability?

Key to answering these questions is to fly a spacecraft, appropriately equipped with instruments designed to measure auroral particles and fields, through the auroral regions of the magnetosphere of Jupiter. Such a mission is Juno (see Figure 12), the second mission of the New Frontier Program, planned to be launched in 2011. Juno will test our understanding of auroral physics and whether the fundamental physics we have learned at Earth from DE, Viking, Polar and FAST can be applied at Jupiter. In the meantime, the New Horizons gravity-assist flyby in spring 2007 will provide a unique opportunity to measure particle fluxes as it flies over 1000 Rj down the magnetotail.

**Acknowledgements**

The author thanks the organizers of the Yosemite 2006 meeting for the opportunity to talk about the magnetosphere of Jupiter. She acknowledges support from NASA’s New Horizons and Juno missions as well as Outer Planets Program (NNG05GH45G).

**References**


Cowley, S. W. H., E. J. Bunce, Modulation of Jupiter’s main auroral oval in Jupiter’s coupled magnetosphere-ionosphere system, Planet. Space Sci. 51, 57, 2003b


Hill, T. W., and V. M. Vasyliunas, Jovian auroral signature of Io's corotational wake, J.
Schneider, N., F. Bagenal, Io’s neutral clouds, plasma torus and magnetospheric interaction, in Io After Galileo, R. Gautier-Lopez, J. Spencer (eds), Elsevier Press 2006
Stefffl, Andrew J., Stewart, A. Ian F., Bagenal, Fran, Cassini UVIS observations of the Io

**Figure Captions**

Figure 1 - The magnetosphere of Jupiter is ~100 times the scale of the terrestrial magnetosphere, encompasses the four Galilean satellites, is filled by plasma from Io and is dominated by rotation. (Inset courtesy John Spencer)

Figure 2 - The interaction of magnetospheric plasma with Io's atmosphere. (a) A 3-D view showing the field-aligned currents that couple Io to Jupiter and the region of plasma stripped directly from Io’s ionosphere. (b) View looking down on Io with the Sun to the bottom of the page and Jupiter to the top.

Figure 3 - (*Above*) Sketch of the Io plasma torus and Jupiter's inner magnetosphere (courtesy John Spencer). (*Below*) EUV emission from the Io plasma torus observed by the Cassini UVIS instrument (Steffl et al. 2004) and synchrotron radio emission from the radiation belts of Jupiter (Bolton et al. 2004) shown to scale.

Figure 4 - Elemental composition and charge state of ions (at ~100 keV) at Earth, Jupiter and Saturn taken by the Charge Energy Mass Spectrometer (CHEMS) when Cassini flew by Earth and Jupiter and then entered orbit about Saturn (Hamilton et al. 2005). (The double blobs in the plot for the molecular ions H$_2^+$ and O$_2^+$ at Saturn are the result of molecular ions breaking up into their atomic constituents upon passing through the carbon foil of the detector.

Figure 5 - The Khurana model of the magnetic field of Jupiter includes components from the internal planetary dynamo, from currents flowing in the equatorial plasma disk as well as on the magnetopause (based on Khurana 2001; Khurana & Schwarzl 2005).

Figure 6 - Major current systems of the magnetospheres of Earth and Jupiter (adapted from Khurana 2001).
Figure 7 - Hubble Space Telescope (STIS) observations of the jovian aurora from the campaign when Cassini flew past Jupiter in Dec. 2000. The projected view is from above the CML at +60 deg. latitude, looking down on the planet. The blue region is from a single image, red is the average of all images during the campaign. Courtesy D. Grodent and J. Clarke.

Figure 8 - (top) Hill’s (1979) original description of the currents system due to mass-loading in the magnetosphere. (bottom) Auroral current system driven by radial transport of plasma from the source at Io. Adapted from Cowley et al. (2002) and Mauk et al. (2002).

Figure 9 - (top) HST/STIS image of jovian aurora (Grodent et al. 2003). (bottom) The Io footprint and wake emissions are related to the Io interaction and currents associated with accelerating fresh plasma up to corotation (adapted from Ergun et al. 2006).

Figure 10 color in both printed and online versions – please!

Figure 10 - (Top left) UV image of the northern aurora taken with the Hubble Space Telescope (ref). Polar, equatorial and side views of the outer magnetosphere illustrate the three main dynamical regions: blue - the rotating plasma disk where lag behind strict corotation drives upward currents and the main aurora; pink - the compressible "cushion region" whose outward motion on the dusk side drives strong currents and the active dusk polar aurora and whose inward motion on the dawn side reduces the load on the ionosphere producing a dark region in the dawn polar aurora; green - the extent of magnetic flux open to the solar wind is not well-known, nor is the extent of convection driven by dayside/tail reconnection in a Dungey-type cycle. Dark green blobs indicate plasmoids ejected down the magnetotail, resulting from reconnection of the tail plasma sheet. The relative importance of large, eruptive plasmoids vs. quasi-steady, small-scale plasma loss mechanisms is not understood.

Figure 11 – Summary of the sources and losses of mass in the jovian magnetosphere.

Figure 12 – Schematic of what we might expect when Juno flies over the pole of the magnetosphere of Jupiter. (Above) Three main regions of plasma processes based on experience from Earth – Alfvenic currents, upward current regions and downward current regions; (below) The trajectory of Juno flies over the poles of Jupiter and passes close above the cloud tops at the equator, avoiding the hazardous region of high energetic electron fluxes associated with the synchrotron radiation belts.
Io Plasma Torus
UV emission

Radiation belts - synchrotron emission
Khurana Magnetic Field Model
Interior + current sheet + magnetopause
Three Types of Aurora

- Polar Aurora
- Main Oval
- Io wake
- Io footprint
How Much of Polar Flux is Open?

How important is the Dungey Cycle?
Mass Budget
1-3 ton/s Io source
1/2-2/3 charge exchange loss as fast neutrals
1/3-1/2 ionized & transported outward

Loss Down Tail:
<0.2 ton/s plasmoid events w/aurora

Remainder:
- small plasmoids
- diffusive "drizzle"
- planetary wind