Dynamics of the Jovian magnetosphere for northward interplanetary magnetic field (IMF)

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[1] A massive rotating equatorial plasma sheet dominates Jupiter’s magnetosphere and the solar wind and the interplanetary magnetic field (IMF) are not thought to be as important as at Earth. We simulated the Jovian magnetosphere for northward IMF starting from a steady state for southward IMF. About 46 hours after the northward IMF reached the dayside magnetopause reconnection started in the Jovian magnetotail and a plasmoid was launched tailward. This was followed by the formation and ejection of three more plasmoids. In each case the reconnection line (X-line) moved tailward with the plasmoid. Magnetic flux tubes from the X-line moved toward and around Jupiter ending up back in the plasma sheet where they were available for additional reconnection. A new reconnection line then formed, a plasmoid was ejected and the process repeated. These phenomena occurred with an average period of 34.3 hours.

[2] The overall configuration and dynamics of the Earth’s magnetosphere are largely controlled by the solar wind and interplanetary magnetic field (IMF). Unlike the Earth, Jupiter’s magnetospheric configuration is determined by a combination of the solar wind, rapid atmospherically driven rotation, a huge magnetic field and plasma from the moon Io. The relative importance of the solar wind and internal processes at Jupiter is not fully understood, (see Cowley et al. [2003] for recent discussions of ionospheric flow dynamics).

[3] So far, seven spacecraft have probed the Jovian magnetosphere (Voyager 1/2, Pioneer 10/11, Ulysses, Galileo and Cassini). Thanks to the database from these missions we now have a good picture of the overall configuration of Jupiter’s magnetosphere [e.g., Joy et al., 2002]. Plasma convective flow in much of the Jovian magnetosphere was modeled on a 602 grid with grid spacing of 1.5Rj. In the simulation the magnetic field (B), velocity (v), mass density (ρ) and thermal pressure (p) are maintained at solar wind values at the upstream boundary (x = 300Rj) while free boundary conditions through which waves and plasmas can freely leave the system are used at the downstream (x = −600Rj). Symmetry boundary conditions are used at the equator (z = 0). At the inner magnetospheric boundary all of the simulation parameters (B, v, ρ, p) are fixed for r < 15Rj. The simulation quantities are connected with the inner boundary through a smooth transition region (15 < r < 21Rj). In particular the velocity is purely rotational and the pressure and density are set to values determined from the Voyager 1 flyby of Jupiter [Beicher, 1983]. The magnetic field is fixed to values from Jupiter’s internal dipole. In the simulation, 2.4 x 1029 AMU s⁻¹ pass through a surface at 22.5Rj into the Jovian system. This value is somewhat lower than the estimate by Hill et al. [1983] but it is within the range of expected values.

2. Simulation Model

[4] Our simulation model of Jupiter’s magnetosphere has been described by Ogino et al. [1992, 1998]. The Jovian magnetosphere was modeled on a 602 x 402 x 202 point Cartesian grid with grid spacing of 1.5Rj. In the simulation the magnetic field (B), velocity (v), mass density (ρ) and thermal pressure (p) are maintained at solar wind values at the upstream boundary (x = 300Rj) while free boundary conditions through which waves and plasmas can freely leave the system are used at the downstream (x = −600Rj). Symmetry boundary conditions are used at the equator (z = 0). At the inner magnetospheric boundary all of the simulation parameters (B, v, ρ, p) are fixed for r < 15Rj. The simulation quantities are connected with the inner boundary through a smooth transition region (15 < r < 21Rj). In particular the velocity is purely rotational and the pressure and density are set to values determined from the Voyager 1 flyby of Jupiter [Beicher, 1983]. The magnetic field is fixed to values from Jupiter’s internal dipole. In the simulation, 2.4 x 1029 AMU s⁻¹ pass through a surface at 22.5Rj into the Jovian system. This value is somewhat lower than the estimate by Hill et al. [1983] but it is within the range of expected values.

3. Simulation Results

[5] For this simulation we gradually reduced the solar wind dynamic pressure to p = 0.01 nPa while the IMF was held constant (Bz = −0.105 nT). The dynamic pressure used in this simulation was near the minimum observed by spacecraft near Jupiter, we selected it to give us a large
magnetosphere in which the middle magnetosphere region covered many grid points. The southward IMF simulation was run until a quasi-steady magnetosphere resulted. Then a northward IMF ($B_z = 0.105$ nT) was imposed. Reconnection began in the plasma sheet at $t = 386$ hours (about 46 hours after the IMF turned from southward to northward) and a plasmoid (magnetic O-region) was launched down the near-tail. In Figure 1 we have plotted the location of the X- and O-lines at the beginning of the events indicate that reconnection began earlier in the previous interval.

![Figure 1](image)

**Figure 1.** Locus of the X-type and O-type neutral lines versus time. The points are plotted every 3 hours. The slight separations in the positions of the X- and O-lines at the beginning of the events indicate that reconnection began earlier in the previous interval.

We can understand the difference between the Jupiter and Earth simulations by considering the plasma flow. At Jupiter, flow from the X-line acquires rotational velocity as it moves toward Jupiter. The plasma is carried around Jupiter and then comes back to the tail. Because the rotation is slower than full corotation it takes longer than one 10-hour Jovian rotation period to go all the way around Jupiter. The velocity is not purely rotational but the azimuthal component is usually largest. For instance at noon near the magnetopause the azimuthal velocity ($V_\phi$) is 180 km s$^{-1}$ to 240 km s$^{-1}$ while the radial velocity ($V_r$) is $-10$ km s$^{-1}$ to 120 km s$^{-1}$. The rotated plasma from the reconnection ends up back in the tail Jupiterward of the old reconnection site. In this phase, the position of the X-type reconnection line in the tail gradually moves tailward. Then, with the addition to the tail of newly opened field lines from the dayside, a new reconnection line appears in the accumulated plasma of the plasma sheet, forms a new plasmoid and ejects it tailward. This process repeats to generate periodic tail reconnection and tailward propagation of both of the O-type neutral line (plasmoid) and old X-type reconnection line. In contrast at the Earth, the plasma convects earthward to the dayside and is carried from the dayside to the tail over the polar cap by dayside reconnection.

[6] We have plotted magnetic field lines in the x-z plane for the interval from 465 hours to 490 hours in Figure 3. There are four types of field lines present. Closed field lines with both ends linked to Jupiter are green. Open field lines with one end at Jupiter and the other extending outside of the simulation box are magenta. Detached field lines that cross the equator twice are red, and detached field lines that cross the equator once and exit from the downstream end of the simulation box are blue. We have divided the reconnection events into four phases. Each panel in Figure 3 represents one of those phases. During the first phase plasma accumulates in the tail. The snapshot at $t = 465$ hours was taken just as the X-O pair formed. In the second phase a small magnetic island caused by reconnection of closed field lines appears. Next, a plasmoid is ejected tailward and there is a sudden enhancement of the Jupitertoward flow. During this phase lobe reconnection begins. Finally during

### Figure 2.

**Figure 2.** (top) Locus of the X-type and O-type neutral lines and (bottom) flow velocity of earthward and tailward flow versus time in the Earth’s magnetosphere [from Ogino et al., 1994].
the fourth phase the plasma flows around dawn to the
dayside and then around dusk back to the nightside. The
velocity of plasmoid ejection is $\sim 495 \text{ km s}^{-1}$ or $25 R_J \text{ hr}^{-1}$
at $400 R_J$ near midnight. These 4 phases repeat periodically.

[9] We show the magnetic field, temperature and plasma
velocity in the equatorial (bottom) and dawn-dusk meridian
planes at $t = 478$ hours in Figure 4. Both plots give the
plasma temperature as a color spectrogram with flow
vectors plotted on top of the color shading. The black
region near Jupiter is inside of the inner magnetosphere
boundary and is not included in the calculation. In the
dawn-dusk plane, the plasma temperature on the duskside
is higher than that on the dayside. In the tail, the
tailward flow associated with the new X-O pair pushes
the previous X-line tailward (bottom). The Jupiterward flow
from the X-line convects toward the dayside (bottom). At
this time the O-line is $\sim 200 R_J$ down the tail. It is curved
toward Jupiter. The most obvious feature of Figure 4
(bottom) is the crescent moon shaped distribution of high
temperature (A). This high temperature flow channel results
from a combination of the tension on stretched dusk side
field lines, the Jupiterward flow from the reconnection and
atmospherically driven rotation.

[10] In Figure 5 the energy flux and flow vectors have
been mapped along magnetic field lines to the ionosphere.
The energy flux is given by $pv$ where $p$ is the pressure and $v$
is the thermal velocity. The plasma parameters were
evaluated at the inner boundary of the simulation and
mapped along magnetic field lines to the ionosphere. The
numbers 00, 06, 12, and 18 indicate the local time (LT). In
Figure 5 corotational flows are dominant up to near the
pole. The influence of dayside reconnection can be seen by
tailward flow near noon. The reconnection driven flows
combine with rotation to form a large counterclockwise cell
over the polar region. This dawn side cell has grown at the
expense of the duskside cell. The constriction near 85
degrees LT, (i.e., between the dayside and duskside) is a
projection of the narrow channel that starts at about 15 LT in
Figure 4. The energy flux to the ionosphere on the duskside
is greater than that on the dayside. The area of greatest
energy flux (yellow) is in between 14 LT and 16 LT.

4. Discussion

[11] We have sketched a mechanism for the periodic
variation of Jovian magnetotail dynamics in Figure 6.
Following a northward turning of the IMF tail, reconnection occurs and plasma is ejected toward Jupiter. When it reaches the middle magnetosphere it is accelerated toward corotation. Then the plasma rotates around Jupiter and accumulates in the premidnight tail. Finally a new neutral line is formed following the addition of new open field lines. The new X-line is stagnant for 15 hours or so. Then it starts to move tailward slowly (171 km s\(^{-1}\)) before a new O-line is formed. The tailward flow from the new X-O pair pushes the old X-line tailward and accelerates its tailward retreat.

Tailward and Jupiterward flow bursts observed by the Galileo Energetic Particles Detector (EPD) reoccur every 48 to 72 hours [Woch et al., 2002]. It is not yet clear whether the observed flow bursts are related to the plasmoid emissions found in the simulation since the simulated period was 32–37 hours. In the simulation the X- and O-lines form at \(x \approx -120R_J\). Galileo observed the flow bursts at distances of 95\(R_J\)–125\(R_J\) in the tail and the flow bursts were both Jupiterward and tailward [Woch et al., 2002]. Thus the X-line in the simulation is at the outer edge of the observed flow reversals.

In the simulations the convective flow time determines the period of plasmoid emissions. The convective flow time in turn is determined by a combination of tail reconnection and rotation of the reconnected plasma. The solar wind, the IMF and the density of Jovian plasma influence the tail reconnection and acceleration of the reconnected plasma toward corotation. First let us consider how the solar wind and IMF can affect the convective flow time. The magnitude of the IMF affects the reconnection rate and the direction of the IMF controls where the reconnection occurs. That varies the solar wind plasma supply into the magnetosphere and solar wind driven convection. The solar wind dynamic pressure as well as the IMF can affect the location and timing of reconnection in the tail. For instance when the dynamic pressure increases the magnetopause moves toward Jupiter and we find that the location of the tail reconnection also moves toward Jupiter. The average dynamic pressure at Jupiter is 0.1 nPa and the average IMF is 0.8 nT [Joy et al., 2002]. The dynamic pressure used in the simulation (0.01 nPa) was lower than that typically observed as was the magnitude of the IMF (0.105 nT).

To investigate the effects of a stronger dynamic pressure and larger IMF, we examined the results from a simulation with solar wind dynamic pressure of 0.09 nPa and northward IMF of 0.42 nT. In this case a pair of plasmoids (first a small one and then a larger one) formed only about 19 hours apart. The X-line was at about 90\(R_J\). After they retreated tailward, another pair of plasmoids formed. These too formed about 19 hours apart at about 100\(R_J\) and they too were ejected tailward. This entire process repeated with a period of 62–72 hours.

Another factor that may influence the period of the plasmoid ejection is the length of time the IMF is northward. In this simulation the IMF was held northward for a long time (185 hours). The IMF observed on Voyager 2 near Jupiter kept one sign of \(B_Z\) for a week and intervals with one sign for 3 or 4 days have been observed a number of times [Walker et al., 2001]. However, usually the IMF varies on shorter timescales. In addition the IMF usually has x and y components in addition to \(B_Z\). The plasma ejection period may be longer when the Jovian magnetosphere is simulated under more common IMF conditions.

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References


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