Nature of magnetic fluctuations in Saturn’s middle magnetosphere


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The saturnian magnetosphere contains a rich array of plasma wave and MHD wave phenomena. These waves are fed by mass loading in the region of the E ring starting with Enceladus at 3.9 Saturn radii (Rs). In this paper we examine the nature of these waves in what we term to be the middle magnetosphere from just outside the mass loading at Enceladus to just inside the region of the magnetodisk, roughly 5 Rs to 15 Rs. In the inner part of this region are ion-cyclotron waves near the water group gyrofrequency associated with mass loading of the magnetosphere by the E ring neutral torus that produces a ring beam of water group ions in velocity space. At about 5.5 Rs, isolated flux tubes are seen that appear to be convecting outward containing cooler plasma. This is a region of high levels of compressional noise. The compressional fluctuations associated with isolated flux tubes never completely disappear but their amplitude diminishes with distance. Weak mirror mode waves are present even at 5 Rs. Those waves grow with increasing radial distance, become dominant, and then the ion cyclotron waves weaken. While both instabilities grow from the same pressure anisotropy, the mirror mode dominance at large distances may be due to the fact that the ion cyclotron waves propagate out of the wave growth region, while the mirror mode waves remain in it and convect with the plasma. Finally, around 12 Rs the magnetosphere switches to be turbulent, more strongly in the transverse component than in the compressional component.


1. Introduction

[2] The Cassini mission allows us to explore plasma instabilities and turbulence in a rapidly rotating magnetosphere to a much greater extent than was possible in the jovian magnetosphere with Galileo because high temporal resolution data are available all along the trajectory, not just in limited regions, such as near satellite encounters. There are many similarities between the two magnetospheres, as well as some important differences. Both magnetospheres have a source of free energy for the generation of waves provided by the ion pickup process. At Jupiter this source is centered at the moon Io [Kivelson et al., 1996], while at Saturn the ions are produced over the much wider radial range of the E ring torus with an enhancement at Enceladus and possibly the other moons as well [Dougherty et al., 2005, 2006; Leisner et al., 2006].

[3] The mass added to the jovian magnetosphere by Io is generally believed to be about 1000 kg s$^{-1}$ [Hill et al., 1983], with direct measurements of the plasma and the waves near Io indicating a value of about 300 kg s$^{-1}$ [Bagenal, 1997; Huddleston et al., 1998]. These estimates are not necessarily in disagreement because the region in which ion cyclotron waves are seen extends far from Io, most likely due to the presence of a fast-neutral population created by charge exchange in the pickup ion population after acceleration by the corotational electric field [Russell et al., 2001]. Thus a fraction of the picked-up ions may be transported across magnetic field lines to become reionized far from Io, and some may even totally escape from the jovian system. The ions that are produced inside the magnetosphere build up in density until the centrifugal force is sufficient to drive radial transport, taking loaded flux tubes to the tail to be dumped, and returning empty flux tubes into the inner magnetosphere to be loaded again [Vasyliunas, 1983; Russell, 2001, 2004].

[4] The ionic mass added to the saturnian magnetosphere by its moons and the E ring is much less than at Jupiter. While estimates based on the flow deflection and an estimate of the conductance of the ionosphere are as high as 100 kg/s [Tokar et al., 2006], the observation of ion-cyclotron waves provides a lower limit to the mass loading rate of under 10 kg s$^{-1}$ [Leisner et al., 2006]. The density of the saturnian magnetodisk (C. S. Arridge et al., The mass of Saturn’s magnetodisk, submitted to Geophysical Research Letters, 2006, hereinafter referred to as Arridge et al., submitted manuscript, 2006) is roughly two orders of magnitude less than that of Jupiter [Russell et al., 1999a; Russell, 2001], consistent with the implications from the wave observations. Because of its smaller size and the more benign energetic particle environment, it is possible that a...
larger fraction of particles leave the saturnian system as fast neutrals than at Jupiter. Thus the pickup rate estimated from the energy flux of ion-cyclotron waves [Leisner et al., 2006] and the magnetic stress tensor (Arridge et al., submitted manuscript, 2006) may underestimate the total mass loss at Saturn more than at Jupiter. Unfortunately, at both planets we have only estimates of the fluxes of the high-energy escaping neutrals and not the fluxes near the energy of the corotating plasma.

[5] We are interested in the nature of magnetic fluctuations in the saturnian magnetosphere for many reasons. As noted above, electromagnetic waves allow estimates of the mass addition rate because a fraction of the pickup energy of the particle is released as an electromagnetic ion-cyclotron wave [Huddleston et al., 1998]. Measuring the Poynting vector or electromagnetic energy flux of these waves, allows an estimate of the total energy being added as new magnetospheric ions and hence the number of new ions added. However, the same particle distribution may release its energy as mirror mode waves when ion beta is significant in the presence of a small (>5%) component of heavy ions [Russell and Farris, 1995]. Thus it is of interest to determine the relative strength of these two wave types.

Figure 1a. One-minute samples of the magnetic field in RTP or radial (out), theta (down), phi (east) coordinates for the inbound pass on Rev. 19. Vertical lines denote intervals studied in greater detail in this paper.

Figure 1b. High pass filtered plot corresponding to Figure 1a. Corner frequency is 0.2 mHz.
[6] The nature of the fluctuations is also diagnostic of macroscopic as well as microscopic (wave-particle) processes. We expect that the radial transport, which results from ion mass loading deep in the magnetosphere, will be unsteady even if the dumping process, which we expect is due to occasional reconnection events, were not unsteady. If all flux tubes were identical, we could not track this process magnetically, but we find that neighboring flux tubes do differ. Some have higher plasma pressures and compensatingly lower magnetic pressures than their neighbors [Leisner et al., 2005]. We note that while the difference between the magnetic field strength of neighboring flux tubes indicates that the plasma populations of the tubes are different, it requires further study to determine if the density of the plasma is greater or less than the density in the tube with the weaker magnetic field. In the isolated tubes in the jovian magnetosphere the tubes with enhanced field strength appear to be depleted of plasma [Russell et al., 2000, 2005], while the tubes studied by Leisner et al. [2005] and confirmed by Burch et al. [2005] to have reduced field strength were judged to be the ones depleted of plasma. No matter which tubes have the higher mass content, identifying where such isolated tubes appear is important because it identifies where flux tubes may be “interchanging.”

[7] While the interchange of flux tubes with different plasma betas creates a low-frequency compressional fluctuation, we also may find low-frequency transverse fluctua-
tions in a planetary magnetosphere with plasma circulation without interchange. In the Earth’s magnetosphere, such field-aligned currents may be quasi-stationary at times of steady (southward IMF) solar wind conditions [Russell and Fleishman, 2002], but in the jovian and saturnian magnetospheres we expect that the outward radial transport, coupled to the rotating ionosphere, results in unsteady field-aligned currents as flux tubes move outward, slow down azimuthally due to angular momentum conservation, and then are tugged back up to corotation velocities by current systems closing through the ionosphere. These unsteady transverse waves were seen by Galileo in the jovian magnetosphere [Russell et al., 1999b].

Because of the important diagnostic role of magnetic fluctuations in identifying the nature of processes occurring in planetary magnetospheres, it is important to establish the

Figure 2a. Three components of the magnetic field and total field for interval a in Figure 1c. One-second data linearly detrended with the average removed are shown in RTP coordinates. Power spectrum shows the compressional power calculated from the total field and the transverse power (total power minus the compressional).

Figure 2b. One-second data for interval c of Figure 1c. Other comments of Figure 2a caption apply.
strength and location of the various fluctuations types in the saturnian magnetosphere. In view of the great volume of data returned by Cassini it is not possible to survey the entire mission database and prepare a timely overview report. Rather we base this overview on the detailed examination of a single orbit, using 48 hours of data centered on periapsis, on Rev 19 (Cassini orbits are labeled beginning at apoapsis). Several other orbits have been examined to verify the generality of the conclusions reported here, but for clarity of exposition we restrict the examples to a single continuous pass through periapsis.

2. Measurements

As our purpose is to provide an overview of the nature of the magnetic fluctuations as an entry to future multi-instrument studies, we restrict ourselves here to an examination of the magnetometer data. Cassini carried two different magnetometers, a fluxgate magnetometer and a vector/scalar helium magnetometer [Dougherty et al., 2004]. These sensors are mounted on a long boom to distance themselves from spacecraft fields. For the purpose of this study it does not matter which magnetometer is used. We choose to examine the fluxgate magnetometer measurements. We also restrict ourselves here to two time resolutions: 1-min averages and 1-s averages. We use KRTP coordinates throughout the analysis “Krono” or K indicates that the center of the system is centered on Saturn. The first coordinate direction, R, is radially outward, T (for theta) is downward and P (for phi) is azimuthally eastward in the direction of rotation.

[10] Figure 1a shows the 1-min data on the inbound leg of Rev 19. The $B_r$ and $B_{\phi}$ components are close to zero, consistent with the near rotationally symmetric, internal field of Saturn and the equatorial location of the spacecraft on this orbit. The total field and the $B_\theta$ component are plotted on the same scale and are nearly indistinguishable, consistent again with the equatorial location of Cassini. Some features are barely visible in this plot. To be able to examine them in greater detail, we will first high-pass filter the data with a corner frequency of 0.2 mHz. This allows the fluctuations to be displayed on a larger scale as shown in Figure 1b but at the same temporal scale. The vertical lines labeled “a to g” are the centers of 30-min intervals for which we display the 1-s data. These 1-s traces are shown for the total field only in Figure 1c. These intervals have been linearly detrended but not filtered in any other way. Later figures will also show the three components of the field in KRTP coordinates as well as power spectral density plots of the 1-s data. The power spectral densities are created using a fast Fourier transform algorithm on the analyzed intervals (30 min unless otherwise stated). These power estimates are summed in overlapping bands of 11 (in this paper) to obtain a statistically accurate spectrum at some sacrifice in spectral resolution. The power in total field (the compressional power) is displayed separately from the sum of the powers on the three sensors less the power in the total field (the transverse power).

3. Inbound Pass: Overview

The data analyzed are from Cassini Revolution 19 beginning at 1800 on 23 December 2005 and continuing to a similar distance on the outbound leg. We do not examine the 6 hours surrounding perikron as the ion cyclotron waves in this region have already been extensively discussed [Leisner et al., 2006]. Perikron was close to 2100 on 24 December and the inbound pass cuts through the dayside magnetosphere. In the KRTP coordinate 1-min magnetic field display in Figure 1a, one can see several flux tubes that stand above the level of the surrounding field on the $|B|$ and $B_\phi$ plots. These are more evident in Figure 1b that displays a high-pass filtered version of the data in Figure 1a. We see an important difference in the compressional noise in the first and second halves of this plot. Initially, from 1800 through 0600 UT on 24 December, the fluctuations are transverse but later, maximizing about 1000 UT on 24 December, the fluctuations are strongly compressional. 

![Figure 2c. Transverse and compressional power spectra for the left side of Figure 2b.](image-url)
We interpret the former, transverse fluctuations as due to field-aligned currents and magnetosphere ionosphere coupling. We attribute the latter compressions to the interchange instability. We note that the equatorial location of Cassini makes it easier to detect compressional than transverse fluctuations if these fluctuations are symmetric about the equator.

We have selected seven half-hour periods in which to display the compressional component with 1-s data. The centers of these periods are indicated in Figures 1c, panels a and b with vertical lines labeled a to g. These linearly detrended 30-min segments are shown in panel c. The top segments (starting at “a”) are closest to Saturn. These segments illustrate the behavior of the high temporal resolution magnetic field fluctuations that are dominated by ion cyclotron waves in panels a and b near 5.13 Rs and 5.35 Rs. Further out, in panels c and d, one sees isolated “cold” flux tubes that in general have very sharp sides. The larger event in panel d illustrates the difference in wave properties inside and outside of the tube, consistent with the presumably different plasma properties. Eventually, the cold flux tubes disappear (panel e) and (panel f) the dominant wave
becomes the mirror mode wave. We identify the mirror mode wave by its compressional nature and characteristic waveform. As we mentioned above, this transition from ion-cyclotron waves to mirror mode waves is reasonable, if the plasma beta is increasing, since mirror mode waves can become more unstable than ion-cyclotron waves under high beta conditions, greater than 2, when a significant (>5%) component of heavy ions is present [Russell and Farris, 1995]. Furthermore, ion-cyclotron waves propagate out of the equatorial plane while mirror mode waves should stay in the equatorial plane allowing a longer growth time. In addition, if the plasma is moving radially outward, the mirror mode waves will be carried outward with the plasma explaining their presence without ion cyclotron waves being present. In panel g there is another period of upgoing flux tubes, but these tubes appear to have less sharp edges than the ones in panels c and d, and, then as shown in panel b, these isolated tubes disappear.

4. Inbound Pass: Waveforms and Spectra

[13] Figures 2a, 2b, 2d, and 2e show the three linearly detrended components (and overplotted total field strength as before) for four of the periods selected in Figure 1c. Figure 2a shows waves dominated by water group ion-cyclotron waves. The waveform shows a strongly modulated amplitude. The wave spectrum on the right has been calculated for the compressional and transverse power

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**Figure 3a.** One-minute samples of the magnetic field in RTP coordinate for the outbound pass on Rev 19. Vertical lines denote intervals studied in greater detail in this paper.

**Figure 3b.** High pass filtered plot corresponding to Figure 3a. Corner frequency is 0.2 mHz.
The waves are predominantly transverse with a well-defined peak power with a second peak at about one-eighth of the water-group gyrofrequency. We do not know the source of this wave or other periodic disturbances such as those seen near 7 Rs (between lines f and g) in Figure 1b. It is possible that they are spacecraft related because the sensors have small angular offsets from their nominal directions. When the spacecraft rolls, the nominal pointing direction is used to rotate the data leaving residual oscillations at the roll period. A small peak has been labeled, MM, for mirror mode. A justification for this will be apparent in later panels. Figure 2b shows the three components for the period labeled d in Figure 1c. Two “cold” flux tubes are seen. The difference in the plasma pressure inside and out of these two tubes is about 2 keV/cm$^3$. We see ion-cyclotron waves in the larger of the two events but no mirror mode is evident. The power spectrum shown on the right clearly shows only the ion-cyclotron peak. The plasma conditions in this flux tube must be much different than outside; specifically, the reduced plasma pressure produces a lower plasma beta in the tubes with the higher field strength. Interestingly, the peak of the power occurs close to the local water group ion gyrofrequency in contrast to all other spectra in which the peak power is below this.
frequency. This observation suggests that the waves were generated when the tube was closer to Saturn. Figure 2c shows the spectrum taken from the left-hand side of the time series in Figure 2b. The spike is not included in the spectrum. Ion-cyclotron waves persist, but mirror mode waves dominate the spectrum here. The peak of the ion cyclotron is below the local water group gyrofrequency as expected.

Figure 2d shows the components of the field in interval e and the corresponding spectrum for the period to the left of the spike. As in Figure 2c, the peak of the ion cyclotron waves occurs below the local ion cyclotron gyro-frequency and strong mirror mode waves are seen. Finally, in Figure 2e we show the components and corresponding spectrum of interval f. Here the ion-cyclotron waves are not evident and the waves are strongly dominated by the compressional mirror mode waves. The quasi-periodic, nearly pure compressional, disturbance characteristic of mirror mode waves is clearly evident in the time series.

5. Outbound Pass: Overview

The outbound pass in many respects mirrors the inbound pass despite the fact that it traverses the nighttime magnetosphere. The 1-min data in Figure 3a show that positive-going spikes in the magnetic field are seen as early as 5.7 Rs. This is most evident in the high-pass filtered (1 min) data and the detrended 1-s data in panel d of Figure 3c. In panels e and f of Figure 3c the positive-going flux tubes are the largest as they are in panels d, e, and g of Figure 1c. We would expect to be able to judge the evolutionary path of such structures by examining the sharpness of their boundaries. Comparing tubes at similar distances on the dayside and nightside (panel g of Figure 1c with panel f of Figure 3c), we see little difference in the sharpness of the edges, so there seems to be little evolution as these structures corotate. However, there does appear to be a “softening” of the profiles with radial distances consistent with other evidence that these structures are slowly moving outward, obviously on timescales of many planetary rotations if our inference of flux tube aging is correct. Figure 3b also resembles Figure 1b in the transition from compressional to transverse noise with increasing distance. We interpret the compressional fluctuations as “interchange” or cold flux tubes moving outward from the inner magnetosphere. If the mass-loaded plasma is transported from the region of the E ring to the tail by these isolated flux tubes, this is a much different circulation pattern than that proposed by Vasyliunas [1983] for Jupiter and updated by Russell [2001]. In the more distant (~12 Rs) magnetosphere the transverse “waves” presumably represent the effects of field-aligned coupling the flux tubes to the corotating ionosphere. The magnetosphere may be subcorotating at these distances if outward flow is rapid, as angular momentum must be added to the plasma to maintain the corotation. We again note that it is difficult to measure the field-aligned currents when the spacecraft is near the equator as it is here.

6. Outbound Pass: Waveforms and Spectra

Instead of repeating the discussion of the interchange tubes as seen on the inbound pass, we focus here on the evolution from ion-cyclotron to mirror mode waves. Figure 4a corresponds to panel a of Figure 3c. The ion-cyclotron peak is strong and the compressional mirror
mode peak is very weak. There is also a weak compressional peak near the ion gyro period indicating that the ion-cyclotron waves are not generated exactly parallel to the magnetic field. This could be a propagation effect as they move from high latitudes toward the equator. In Figure 4b, corresponding to panel b of Figure 3c, the ion-cyclotron waves are slightly weaker and the mirror mode waves significantly stronger. In Figure 4c the major change from the previous figure is not in the ion-cyclotron waves but in the mirror mode wave growth. Finally, in Figure 4d the ion-cyclotron waves are again only a little weaker and the growth of the mirror mode waves much stronger so the major change with radial distance in this region is in the mirror mode waves and not in the ion-cyclotron waves. Eventually however, the ion-cyclotron waves do disappear.

[17] We recall that the mirror mode identification here is entirely based on the compressional nature and their characteristic waveform. We do expect that ion-cyclotron and mirror mode waves would be seen at the same time because

Figure 4b. One-second data for interval b of Figure 3c. Other comments of Figure 4a caption apply.

Figure 4c. One-second data for interval c of Figure 3c. Other comments of Figure 4a caption apply.
they arise from the same pressure anisotropy ($P_\parallel/P_\perp > 1$). In fact their joint occurrence has previously been found near Io’s wake [Russell et al., 1999c].

7. Discussion

[18] Our exploration of the magnetic fluctuations on these two segments of Rev. 19, one through the dayside magnetosphere and one through the nightside, shows that there is very little change in the fluctuations with local time inside about 15 Rs. There are changes with distance, however. In the inner part of the region explored near 5 Rs, where we expect the lowest beta plasma we see almost purely transverse, water group ion-cyclotron waves. As we proceed outward from about 5 Rs, mirror mode waves begin to grow. As we approach about 7 Rs, the ion-cyclotron waves disappear and mirror mode waves appear. As mentioned above, mirror mode waves and ion-cyclotron waves grow from the same particle anisotropy ($P_\perp/P_\parallel > 1$), that is expected from ion pickup. These two waves have been seen adjacent to each other at Io where they clearly grew under similar conditions [Russell et al., 1999c].

[19] It is worth reviewing here the pickup conditions at Jupiter and Saturn. Figure 5a plots the various relevant velocities at Jupiter as a function of distance. The dot-dash line shows the keplerian velocity, the velocity of orbiting unionized (neutral) particles. At the orbit of Io where most of the added material originates, this velocity is 17 km s$^{-1}$. The escape velocity at which neutral material will escape the gravitational potential is only 41% higher than the circular orbital velocity. It is shown by the dotted line. The corotational velocity, the velocity of the magnetospheric plasma if it rotates rigidly with the ionosphere, is shown by the solid line. This velocity is 74 km s$^{-1}$ at Io. Thus ions produced from the Io atmosphere are picked up at 57 km s$^{-1}$ at Io. As they gyrate about the magnetic field, the pickup velocity can add and subtract from the average corotational drift. The sum of the two is given as the maximum velocity in Figure 5. Beginning at synchronous orbit, just outside 2 R$_J$, the picked up ions travel faster than orbiting material and not much further out reach (at least at their maximum speed) the escape velocity, and by the time Io is reached the speed of picked up ions is greater than that of escape over most of their gyration. Hence if they do become neutral, these particles generally begin on escape paths.

[20] Figure 5b shows the equivalent plot for Saturn. Saturn is a little smaller and spins a little slower but is much less dense than Jupiter. Hence synchronous orbit is
Figure 5b. Characteristic velocities of the saturnian magnetosphere. Comments of the caption of Figure 5a apply.

relatively closer to the planet, inside 2 Rs. Another important factor is that mass loading occurs inside 4 Rs where the corotational velocity is much less than at Io so that the picked-up ions are less energetic. Nevertheless, we do expect much escape at Saturn as the particle velocities soon reach escape velocity as one moves outward from Saturn. So qualitatively the situation is the same at both planets, albeit with a distributed ion-pickup source at Saturn, and a more confined pickup region at Jupiter.

[21] Mirror mode waves and ion-cyclotron waves grow from the same particle anisotropy (T_\perp/T_\parallel > 1). Which mode dominates depends on several factors, such as plasma beta and plasma background conditions (i.e., composition, gradients). For low beta values, linear theory predicts that the ion cyclotron waves have the lowest instability threshold and grow faster. The solution of the kinetic dispersion relation in a multicomponent plasma similar to the regions where the mirror mode waves are observed (M. F. Thomsen, personal communication, 2006) shows that the growth rate of the two modes can be similar for large beta (>7) and low anisotropy (T_\perp/T_\parallel ∼ 1.5). Table 1 shows three cases we have examined using Ronnmark’s [1982] WHAMP program to determine the wave growth for the two modes. However, such large beta values are not expected to be observed inside Saturn’s magnetosphere. Moreover, the frequency of maximum growth of the ion cyclotron waves drops well below the water group ion cyclotron frequency and this is not observed in the data. Therefore the existence of regions in the E ring environment where the mirror mode dominates suggests that some other factor than simply ion beta can play a role in limiting the growth of the ion-cyclotron instability. The presence of multiple ion species has been found to limit the growth of ion-cyclotron waves near Io and enhance the growth of mirror mode waves [Huddleston et al., 1999]. This occurs because the ion cyclotron modes due to each species depend on a resonance between the waves and the ions present, while the mirror mode is nonresonant and results from the integrated temperature anisotropy over all species present. This same problem has been studied in the Earth’s magnetosheath where strong mirror-mode waves are frequently found. Price et al. [1986] used simulations to predict that the presence of heavy ions would allow mirror mode waves growth to exceed that of ion-cyclotron waves. Russell and Farris [1995] showed that this prediction was correct when beta exceeded 2 and the alpha particle content of the magnetosheath plasma was 5% or greater. However, the frequency of the peak amplitude being close to the water group gyrofrequency is symptomatic of a low beta plasma. As an alternate explanation, we note that the direction of propagation of the waves can have an effect on their amplitude. Ion cyclotron waves have their largest growth at parallel propagation, moving along the field and out of the equatorial source region. Mirror mode waves would not move away from the equator and would grow while being carried radially outward by the plasma. Because this mode does not propagate, mirror mode waves can be in the free energy region a longer time than ion cyclotron waves and their amplitude can be enhanced despite slow growth. Further, they can be carried out of the region of growth where there should be no ion cyclotron waves.

8. Conclusions

[22] Saturn’s middle magnetosphere is rich in wave phenomena. The two most persistent waves are ion-cyclotron waves near the water group gyrofrequency and mirror mode waves at lower frequencies, both presumably driven by strong pressure anisotropies created during the mass pickup from the E ring torus. The dominance of mirror mode waves at greater distances may be due to the combination of the higher beta at greater distances and the presence of a fractional component of heavy ions. Moreover, the ion cyclotron waves escape from the source region while the mirror mode waves should remain in it. This should help the

Table 1. Input Parameters for Dispersion Analysis

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<th>M_\parallel/\rho_\parallel</th>
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<th>N_\text{ring}, m^{-3}</th>
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^N_\text{bg} is background density; N_\text{ring} is ring density; T_\parallel is parallel ion temperature. A is perpendicular to parallel temperature ratio used as an effective anisotropy in WHAMP [Huddleston et al., 1999]; \omega_\text{ciw}/\Omega_\parallel, is frequency ratio at maximum ion cyclotron wave growth, mirror mode growth is at zero frequency; \gamma_\text{mm} is ratio of maximum growth rates. In all cases, magnetic field is 55 nT, electron temperature is 80 eV, and pickup velocity is 59 km/s.
mirror mode waves to grow to significant amplitudes despite their lower growth rate. Interchange is clearly seen as cold flux tubes move outward from the inner magnetosphere. At least at low radial distances the edges of these tubes are sharp and the plasma conditions quite distinct. The evolutionary path of these tubes appears to be that they age with increasing radial distance. If so, then they may provide the outward transport of mass loaded plasma to the tail where the plasma is dumped from the flux tube. This appears to differ from the more homogeneous, rotating, radially drifting, circulation pattern proposed by Vasylunas [1983] for Jupiter. Perhaps such small-scale transport could become more uniform and jovian-like at greater distances. The existence of a saturnian magnetodisk beyond 15 Rs (Arridge et al., submitted manuscript, 2006) is consistent with this picture.

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