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OBSERVATIONAL CONSTRAINTS ON INTERCHANGE MODELS AT JUPITER

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Abstract. Data from the Voyager plasma science instrument is used to set limits on transport models for the inner Jovian magnetosphere. The instrument has an effective time resolution for detecting changes in density of 0.24 s, which corresponds to a spatial resolution of about 20 km (equal to the gyroradius of an oxygen ion) in the region just outside of Io. This resolution enables us to put an upper limit of about 10% on changes in density between adjacent magnetic flux tubes, which rules out transport models which invoke inward motion of near empty flux tubes to replace outward-moving flux tubes carrying Iogenic plasma.

Introduction

As soon as ground based observers discovered the Io torus [Brown, 1974; Mekler et al., 1974; Trafton, 1975; Kupo et al., 1976] models governing plasma transport were produced. The first models [Siscoe and Chen, 1977; Siscoe, 1978] assumed steady state conditions and transport via atmospherically driven diffusion [Brice and McDonough, 1973; Coroniti, 1974] and predicted density maxima well inside Io's orbit. Voyager 1 passed through the torus in 1979, revealing that the actual density profile peaks near Io and drops off very rapidly inside of Io and more gradually outside of Io [Bridge et al., 1979; Bagenal and Sullivan, 1981]. Time dependent models were proposed to explain these features [Richardson et al., 1980], but were discarded as Voyager and ground based spectroscopy indicated that the general structure of the torus is long-lived [Trauger, 1984]. Attempts to model the large gradients in both temperature and density inside of Io using diffusion models have encountered problems [Richardson and Siscoe, 1983], although charge exchange processes involving SO_2 may resolve these difficulties [Moreno and Barbosa, 1986]. Transport outward from Io is much faster than transport inward, which is attributed to the onset of centrifugally driven transport processes outside of Io [Richardson et al., 1980; Siscoe and Summers, 1981]. The theory of centrifugally driven interchange diffusion has been developed by Summers and Siscoe [1985, 1986]; their theory predicts that the unstable interchange mode consists of alternating spiral channels of inward and outward flow, driven by the sharp density gradient at Io associated with the plasma ribbon observed by Trauger [1984]. The size of these channels and the density and temperature variations expected as the Voyager spacecraft passes from inward to outward moving channels are not determined by their theory. An alternate transport mechanism developed by Vasyliunas [1978] and Hill et al. [1981] transports plasma by means of a large scale corotating convection system, with plasma flowing outwards in one longitudinal sector and inwards elsewhere. Pontius et al. [1986] proposed another transport mechanism in which full flux tubes move outward and less dense flux tubes move inward. (This is similar to an earlier model of Mendis and Axford [1974].) They interpret the observed radial decrease in flux tube content [Bagenal and Sullivan, 1981] as due to an increase in the percentage of less dense flux tubes with increasing radial distance. Other transport mechanisms have been proposed by Abe and Nishida [1986] and by McNutt et al. (unpublished manuscript, 1986). The former propose that scattering at a frequency comparable to the ion gyrofrequency leads to diffusion across the magnetic field, unloading the Iogenic plasma from the magnetosphere at a steady rate. McNutt et al. (unpublished manuscript, 1986) suggest that plasma transport in the Jovian magnetosphere may be driven by ballooning-type instabilities.

The Voyager Plasma Science (PLS) instrument samples plasma properties with a time resolution as low as 0.24 seconds. In this paper we discuss limits which this data set imposes on interchange models in the Jovian magnetosphere.

Instrument and Resolution

The PLS instrument has been discussed in detail elsewhere [Bridge et al., 1977] and only a brief summary of points relevant to this paper is given here. The instrument consists of four modulated-grid Faraday cups. All four cups measure ion currents in the energy-per-charge range 10 - 5950 V. One sensor also measures electron current in the same energy range. The instrument covers this energy-per-charge range by stepping through a set of contiguous voltage "windows", or channels, whose widths increase roughly linearly with voltage. Two ion measurement modes are used; the low resolution (L) mode has 16 voltage channels with an energy-per-charge resolution of 29%, the high resolution (M) mode uses 128 voltage channels with an energy-per-charge resolution of 3.6%. The measurement time for each voltage channel at Jupiter is 0.24 s (0.21 s integration time, plus 0.03 s to change the voltage levels), so it takes 3.84 and 30.72 s to obtain complete L and M-mode spectra, respectively. One set of L-mode spectra (measured simultaneously in all four Faraday cups) is obtained every 96 s. One set of M-mode spectra is also measured every 96 s; however, only currents from 72 of the 128 M-mode channels are transmitted during each

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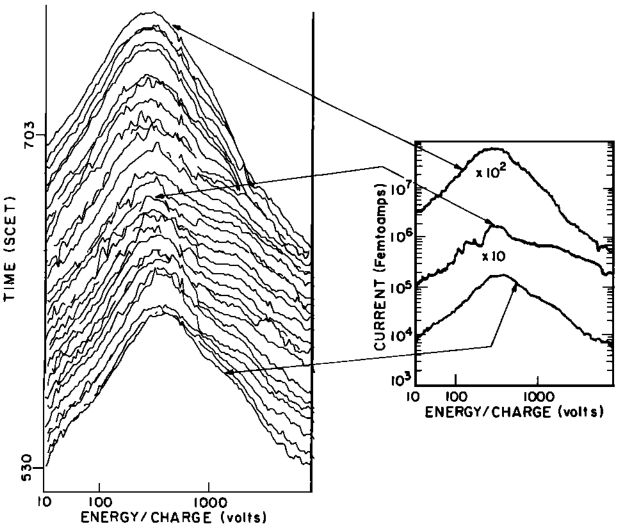

Fig. 1. A logarithmic plot of the ion currents in the side sensor of the PLS instrument as a function of energy measured by Voyager 1 inbound on day 64, 1979 between 0530 and 0703 SCET. Three spectra are plotted to the side to show the magnitudes of the currents.

measurement cycle, so a complete set of M-mode spectra is received on the ground every 192 s.

The instrument resolution thus varies depending on the parameter considered. Determination of most plasma parameters requires a full set of energy-per-charge spectra. Velocity, number density, composition, and temperature determinations have effective resolutions of 96 s for L mode spectra and 192 s for M mode spectra. Changes in the density can, however, be resolved on much smaller time scales. Since changes in density result in changes in the current in each voltage channel, the effective resolution for detecting density variations is the step time of the voltage increments, 0.24 s. We quantify the magnitude of changes which can be discerned in the next section.

Observations

The M-mode spectra in the side looking (D) sensor, which is least affected by interference from other instruments on board the spacecraft, is shown in Figure 1. This figure includes data obtained on March 5, 1979 between 0530 and 0703 SCET (spacecraft event time). This time period corresponds to dipole L shells from L = 9 - 7. Within this period is the sharp drop in flux shell density which has been labeled the "ramp" [Siscoe et al., 1981]. Interchange diffusion is presumed to occur everywhere outside the peak in flux shell density [Summers and Siscoe, 1981], which is located just inside Io's orbit [Bagenal and Sullivan, 1981]. Pontius et al. [1986] hypothesize that the ramp region is where full flux tubes become detached and move outwards independent of each other. Thus Figure 1 contains the appropriate spectra for comparison with these theories.

The spectra plotted cover the full 10 - 5950 eV energy range, with 192 s separating adjacent spectra. Each spectrum contains the first 72 channels from 1 measurement cycle and the last 56 from the previous cycle. This splicing together of spectra in a region where densities are rapidly increasing results in discontinuities in some spectra. There are bumps and wiggles in many of the spectra, but the spectra overall are fairly smooth, especially at high energies. Three spectra have been pulled out to the side so that variations can be quantified. The upper spectrum from L = 7.3 exhibits variations from channel to channel of less than 10%. Thus 10% is an upper limit on the variability within the spectrum due to temporal density changes (time aliasing). The middle spectrum at L = 7.9 has several peaks at low energies but only small variations at higher energies. The peaks may be due to a cold ion component underlying the hot ions; this cold component is often present near current sheet crossings [McNutt et al., 1981]. The bottom spectrum at L = 8.5, just outside the ramp and away from the magnetic equator, is again smooth with current variations of less than 10% from channel to channel.

Implications for Transport Models

There are two transport models we wish to discuss - those of Summers and Siscoe [1985] and Pontius et al. [1986]. Pontius et al. [1986] have proposed that the Jovian magnetosphere outside of Io contains two types of flux tubes, full flux tubes containing outward-moving Iogenic plasma, and empty (or less full) flux tubes which move inwards to compensate. Outside the source the full flux tubes become detached due to an instability analogous to the Raleigh-Taylor gravitational instability and move outwards independently of each other. Summers and Siscoe [1985] derive the fundamental wave modes present in the Io torus. They find that the only unstable wave mode is the inertial interchange mode which consists of alternating spiral channels of inward and outward flow.

Both of these models are based on the equations governing corotating convection which were formulated by Chen [1977] and Hill et al. [1981], the difference being in the shape of the flux tubes used. A basic premise of this set of equations is that the density per magnetic flux is conserved in the absence of local sources and losses. Thus the only way to decrease the longitudinally averaged flux tube content in these models is to increase the percentage of empty flux tubes. The observed flux tube content decreases by a factor of 4 between L = 6 and 9 (Bagenal and Sullivan, 1981). This implies that the density ratio between inward and outward moving flux tubes or channels (used interchangeably from here on in) must be at least a factor of 4 to satisfy these models. The actual size of the flux tubes is not determined by the models. Pontius et al. [1986] have suggested that these flux tubes are too small to be resolved by the PLS instrument. We show that this is not the case, and that density fluctuations of greater than 10% are not present on scales smaller than several Jovian radii.

The gyroradius of an ion with a mass to charge ratio of 16 (the most prevalent ion) at L = 8 is about 20 km. Thus a flux tube must be several times this large to be a meaningful entity. The spacecraft speed relative to the convecting plasma is about 80 km/s; the 0.24 s spacing between voltage channels therefore gives the PLS instrument an effective spatial resolution of 20 km for detecting density variations such as those expected if empty flux tubes are present. This is comparable to the size of a flux tube, so empty flux tubes would be easily detectable if

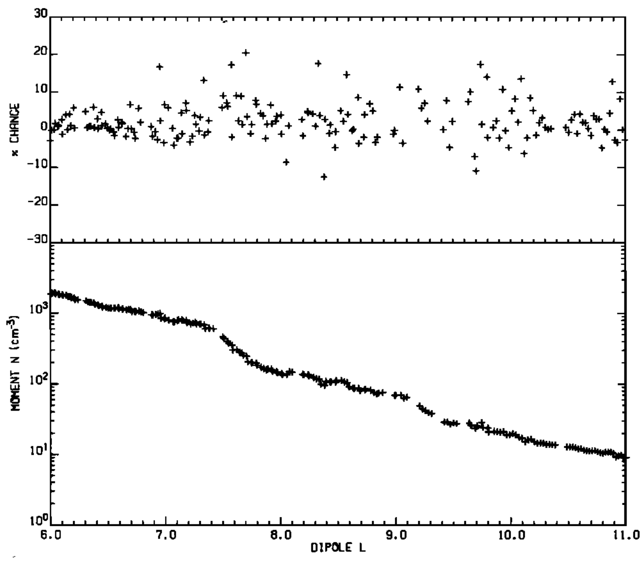

Fig. 2. A plot of moment density (lower panel) and the percentage change in density since the measurement of the previous spectrum (upper panel) plotted versus dipole L.

they were present. For example, an empty flux tube with a radius equal to two gyroradii would be 80 km across, and result in a biteout in the measured current 4 channels in width. Dropouts of this type clearly are not present in the data as shown by Figure 1. Larger flux tubes (distance scales comparable to the integration time for obtaining a spectrum) would result in large variations in current levels from spectrum to spectrum and occasional large discontinuities within a spectrum. Again such effects are not observed. The only way to hide empty flux tubes from our detector is if they were much smaller than 5 km, which is much less than an ion gyroradius and physically unreasonable, or to have them move past the spacecraft in much less than the time required to complete a current measurement. For an 80 km flux tube to move past the spacecraft in 0.024 s (one tenth the resolution of the instrument), it would need a speed of 3200 km/s, much faster than the Alfvén speed. Thus large variations in density over time scales short compared to the PLS resolution can be ruled out.

Both transport models considered here predict outward moving flux tubes which are more dense than those moving inwards, but neither the density difference nor the size of the flux tubes has been determined. These transport mechanisms thus predict that periodically the spacecraft should move through more dense and less dense regions. We attempt to place limits on the size of the density variations allowed by the PLS observations. Clearly the width of these flux tubes must be at least a few gyroradii, corresponding to about 4 of our voltage windows. Variations in the measured spectra on time scales less than this must result from other causes. As discussed above, there is no systematic variation in density over these time scales. If the flux tubes are larger, one would expect to see changes between spectra, and occasional changes within spectra. A flux tube size of 0.1 Jovian radii implies a boundary crossing from inward to outward flow every 6 minutes, or every four spectra; larger flux tube sizes would imply proportionally larger times.

Figure 2 shows a plot of ion charge density and the percentage change in density from the previous spectrum plotted versus dipole L shell. The charge densities shown are derived from a moment calculation (see McNutt et al. [1981] for details) which assumes rigid corotation. Thus the absolute values for the density may be off by 20 - 30%, but the relative density change from spectrum to spectrum should be accurate. The density rises from 10 cm^{-3} at L = 11 up to 2,000 cm^{-3} at L = 6. The percentage change is always less than 21%; the average change per spectrum is +2.2%, with a standard deviation of 5.5%. It is clear that if inward and outward moving flow channels are being encountered, the density variation between these channels is less than about 10%, unless these channels are very large, on the order of a few Jovian radii, so that few boundaries are sampled. This limit is incompatible with both the Pontius et al. [1986] and Summers and Siscoe [1985] transport models.

Summary

The plasma data from the Voyager plasma experiment can be used to set limits on transport models in the Jovian magnetosphere. We have found that models which require density fluctuations of more than about 10% over distance scales of less than a few Jovian radii are not consistent with the data. This rules out models such as that proposed by Pontius et al. [1986] and Summers and Siscoe [1985] which postulate the interchange of empty (or less full) and full flux tubes under the assumption that the density per magnetic flux remains constant.

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