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HIGH RESOLUTION MEASUREMENTS OF DENSITY STRUCTURES IN THE JOVIAN PLASMA SHEET

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Abstract. A recent effort to determine the plasma density by using the low-frequency cutoff of trapped continuum radiation in the vicinity of the Jovian plasma sheet has revealed the existence of sharply defined density structures in the plasma sheet. These structures typically have a plasma density which is relatively constant, but of order 50% greater or less than that of the surrounding plasma. The transitions from low to high density occur on time scales of about ten seconds, which correspond to spatial dimensions of the order of a few ion Larmor radii. Voyager requires time intervals of less than a minute to more than five minutes to traverse the structures themselves, corresponding to size scales from a fraction of a Jovian radius to more than a Jovian radius. The existence of such structures in the Jovian magnetosphere raises obvious questions as to their three-dimensional nature as well as their origin. We suggest that the structures might represent flux tubes of varying plasma content, but on the basis of single-point measurements, we do not have the observations necessary to describe the three-dimensional form of the structures. A Fourier transform of the density variations yields a featureless spectrum which displays an inverse frequency dependence. This spectrum is consistent with the square wave-like form of the density variations observed. The observations of flux tubes in the middle magnetosphere of widely varying plasma content may be the result of a centrifugally-driven plasma transport mechanism acting inwards of the point of observation. We conclude that the structures observed are not consistent with an eddy-diffusion model.

Introduction: Determination of Density From the Continuum Radiation Cutoff

Nonthermal continuum radiation is a common feature of planetary magnetospheres [Gurnett and Shaw, 1973; Gurnett, 1975; Scarf et al., 1979]. This radiation propagates in the free space modes and usually consists of a trapped component, which is trapped in the low-density cavity of the magnetosphere at frequencies below the solar wind plasma frequency, and an escaping component, which can propagate freely away from the planet at frequencies above the solar wind plasma frequency. The trapped component often has a sharply defined low-frequency cutoff at the local electron plasma frequency, which is the cutoff of the free space ordinary mode [Stix, 1962]. When the cutoff is present the electron density can be determined by using the relation

$$f_p = 8.98\sqrt{n_e}\ kHz \qquad (1)$$

where n_e is the electron density in cm^{-3}. Continuum radiation was discovered at Jupiter by Scarf et al. [1979] using the Voyager plasma wave receiver and is the dominant part of the low-frequency radio spectrum. For a discussion of the plasma wave instrumentation, see Scarf and Gurnett [1977]. The technique of finding the electron density from the continuum radiation cutoff was employed for the Jovian magnetosphere by Gurnett et al. [1979, 1981] using data from the plasma wave receivers on board Voyager 1 and 2. Wideband waveform observations provide high resolution spectra of continuum radiation in the Jovian magnetosphere from which the cutoff frequency, and hence, the electron density can be determined. Figure 1 is an example of wideband data obtained 33 Jovian radii (R_J) from Jupiter on the nightside, outbound leg of the Voyager 1 trajectory during a crossing through the plasma sheet. Continuum radiation, with its distinctive lower frequency cutoff, can be seen very clearly near the top of the spectrogram. Our density determination process utilizes a semi-automated technique to find the cutoff frequency every 4 seconds. Only when the Voyager wideband data exist and when the continuum radiation is present with a cutoff in the frequency range between about 50 Hz and 12 kHz, is there the potential for high time resolution electron density determination using our method. These conditions are met for significant portions of the two Jupiter encounters. The wideband observations are obtained in 48-second intervals, called frames, which correspond to the time it takes to transmit a Voyager image. Wideband data compete with imaging data for the telemetry resource. While some intervals have continuous wideband data coverage, such as that in Figure 1, often data are only available for every other or every fourth 48-second frame. Extensive intervals exist where either the continuum radiation is not observed or there are no wideband data at all. It should also be recognized that the cutoff in the continuum spectrum can be caused by high-density plasma between the observer and the source of the radiation, hence the cutoff, strictly speaking, may only be an upper limit to the local plasma frequency. Because the cutoffs observed by Voyager at Jupiter are quite sharply defined, it is likely that they are caused by the local plasma in most cases.

Because of gaps in the data every 60 ms imposed by the nature of the telemetry format, it is natural to Fourier transform the waveforms between these gaps. Hence, the usual processing yields a spectrum every 60 ms. In principle, we could derive a density by analyzing each 60-ms spectrum. For the density data set utilized herein, we decided to use a

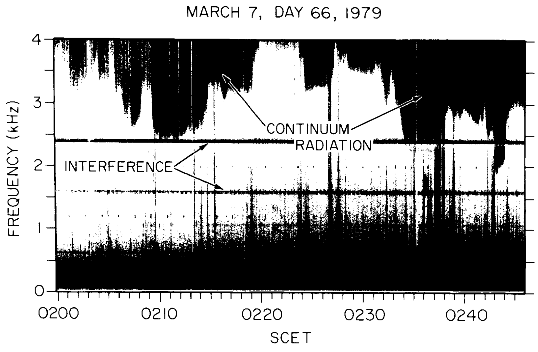

Fig. 1. Wideband spectrogram from the Voyager 1 plasma wave instrument. The darker areas correspond to more intense waves. The sharp boundary between the dark continuum radiation and the lighter region below is the cutoff frequency which is used to identify the local electron plasma frequency during this plasma sheet crossing. Interference at 2.4 kHz is from the spacecraft power supply.

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coarser time scale for several reasons. First, a single 60-ms spectrum is quite noisy, hence, the cutoff is difficult to measure. Averaging over several consecutive spectra reduces this noise. Second, the effort and volume of data required to assemble a complete 60-ms resolution density data set is beyond our resources. Third, an analysis of some of the sharpest density variations showed that a much coarser time interval would still resolve these structures. Consequently, we have selected 4-second temporal resolution as an optimum resolution. For any reasonably limited period of interest we can reprocess the data to obtain any temporal resolution down to the 60-ms resolution inherent in the data stream. This 4-s resolution represents a significant improvement over the 96-s intervals typically used in the analysis of the Voyager plasma instrument's observations [c.f. McNutt et al., 1981].

Observations: Structures in the Jovian Plasma Sheet

The dramatic variations in the cutoff frequency seen in the interval shown in Figure 1 caught our attention early in the process of compiling the density data set. The data set covers many other regions in the magnetosphere, some of which show similar density structures. We will concentrate our attention on the half-hour or so interval shown in Figure 1 where the wideband data are virtually continuous; a discussion of other regions included in the density data set is beyond the scope of the present paper and these other regions will be covered in a more comprehensive paper in the future. The upper panel of Figure 2 shows the cutoff frequency plotted as a function of time. The solid line connects measurements for which we have considerable confidence in the identification of the cutoff frequency. The dashed line appears when the cutoff frequency approaches 2.4 kHz where there is an interference line from the spacecraft power supply as well as a notch filter in the receiver designed to limit the effects of the power supply interference. Near this frequency, it is not possible to accurately identify the cutoff, yet we are reasonably confident the cutoff appears in this region of the spectrum. Occasionally, the spectrum is so noisy that it is not possible to make a reliable measurement of the cutoff, hence, no data are plotted for these times.

For the times indicated by the solid line, the error in measuring the cutoff is typically one or two frequency elements in the spectrum, which are separated by 28 Hz. Hence, the uncertainty in the density measurement is a few percent. To obtain a more quantitative estimate of the uncertainty in the measurements, we had a second individual digitize the continuum radiation cutoff for the interval shown in Figure 1. The densities obtained by this second individual were subtracted from those obtained originally. An average of the absolute value of the differences is 3.0 x 10^{-3} cm^{-3}, or about 3% of the average density in the interval (0.11 cm^{-3}).

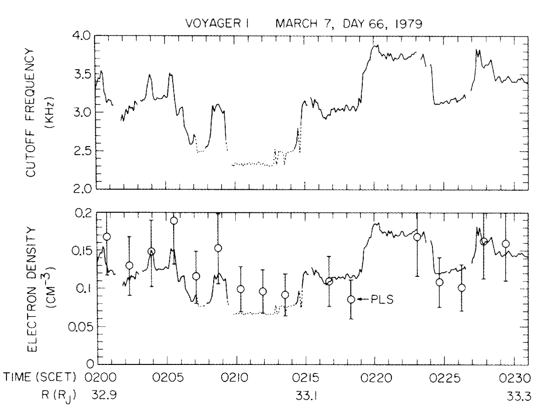

Fig. 2. Thirty-minute segment of data showing the cutoff frequency for each four-second average of the wideband data (upper panel), and the electron density calculated using Equation 1 (lower panel). Superimposed on the density calculations are the in situ measurements of electron density made by the plasma science instrument on board Voyager 1.

The bottom panel of Figure 2 shows the transformation of the cutoff frequencies into electron densities by the use of Equation 1. For comparison, measurements of the plasma density obtained from the plasma instrument (via the Planetary Data System) are superimposed on the density profile measured using the cutoff method. The error bars represent an uncertainty of 30% which is typical of the density determination by the plasma instrument in this region [J. D. Richardson, private communication, 1991]. Note that there is basically no statistical disagreement between the plasma investigation's measurements and those based on the continuum radiation cutoff. Further, the plasma measurements do show the magnitude of density variations apparent in the cutoff data set. However, the 4-s resolution measurements show the almost step-level changes in the densities between these structures. In spite of the sharpness of these transitions, most of them have at least three cutoff measurements across the transition, hence, the transitions are resolved, even without resorting to the much higher temporal resolutions afforded by the wideband data.

The density variations illustrated in the bottom panel of Figure 2 are typically of the order of 50% and the transitions from one density to another occur on times scales of about 10 seconds. The densities are rather constant for periods of < 1 to ~ 5 minutes and have values ranging from 0.08 to 0.2 cm^{-3}. In order to estimate the spatial scales of the sharp density gradients and the density structures themselves, one must have some knowledge of the relative velocity between the spacecraft and the plasma. Since we are only concerned with order-of-magnitude spatial scale estimates in this initial work, we will use a rather arbitrary but not unreasonable velocity estimate for the plasma of half of the rigid corotation velocity [McNutt et al., 1979]. At 33 R_J, this is about 200 km/s. Since the spacecraft speed is only about 10% of the plasma speed, we can ignore it for these purposes. With 200 km/s as a relative velocity, the density structures have scale sizes ranging from 0.1 to an R_J or more. The transitions take place over distances of order 2000 km. For comparison, keV oxygen ions (typical of ions in this region of the magnetosphere [McNutt et al., 1981]) have a Larmor radius of about 1000 km, hence, the density transitions take place over just a few ion gyroradii.

We have made an initial inquiry into the possible relationship between the density structures and variations in the magnetic field. In Figure 3 we plot the density data for the interval in Figure 1 along with the vector components and magnitude of the magnetic field (obtained from the Planetary Data System). The density profile presented here shows that the plasma sheet is very complex and is not simply related to magnetic field variations. It is interesting to note that the density is actually higher at positions out of the current sheet (defined as that time when the radial component of the field goes through 0 at about 0235 SCET) than within it. In fact, the density is higher for almost 20 minutes preceding the current sheet crossing. Generally, a diamagnetic effect is seen when the Jovian plasma sheet is traversed [Ness et al., 1979]. Do the small high density structures shown herein also exhibit a diamagnetic effect? Or, are these density enhancements adiabatically cooling as they expand outward? In spite of the very distinct structures evident in the density displayed in the upper panel, there is very little correlation with either the field magnitude or direction. While some discrete features, such as the density enhancement near 0228 SCET, are apparently associated with a decrease in field magnitude, there is no consistent correlation between the density and field. A complete analysis of this nature, obviously, would address variations in the plasma

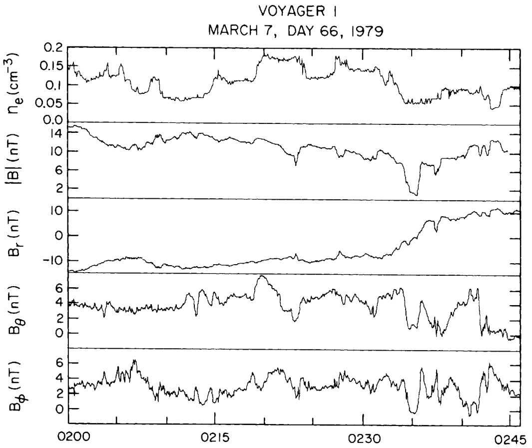

Fig. 3. The density data determined during the 46-minute interval in Figure 1 (top panel) plotted along with the magnetic field intensity and the vector components (lower panels). Little correlation is evident between electron density and the magnetic field during this plasma sheet crossing.

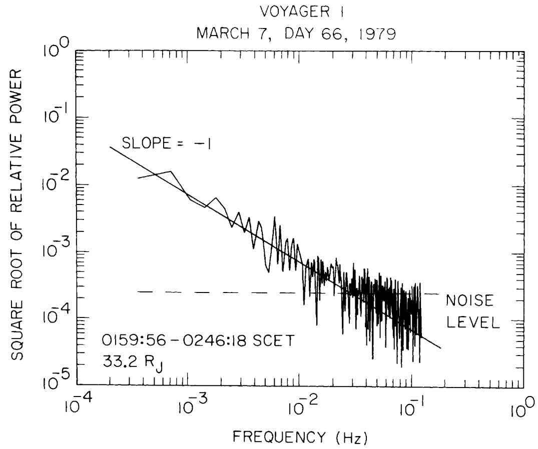

Fig. 4. Fourier transform of the density variations obtained from the 46-minute interval in Figure 1. The point at 3.6 x 10^{-4} Hz corresponds to a period of 46 minutes, while the point near 0.125 Hz corresponds to the Nyquist frequency based on 4-second sampling periods. The line with slope -1 is drawn for comparison.

temperature, as well. One can find evidence in Figure 3 of features in the magnetic field which are consistent with an overly dense flux tube moving outward through a generally less dense plasma. In some of these enhancements, the radial component of the field B_r increases relative to the elevation component of the field B_θ, suggesting the dense tube is being stretched in a radial direction. In other cases, there is evidence that there is a change in the azimuthal component B_ϕ consistent with increased tension in the field enforcing corotation of the plasma. The density peak near 0204 SCET exhibits evidence of both of these effects, for example.

Some of the other time periods covered by the density data set show similar structures, but have less continuous data and are, therefore, more difficult to study. These other density structures have similar time scales and variations in magnitude so, while we concentrate on the specific interval in Figure 2, these structures are not specific to this one region in the Jovian magnetosphere.

Discussion and Conclusions

The volcanoes of Io are generally believed to be the source of copious amounts of plasma, indeed the primary source of plasma, in the Jovian magnetosphere. How this plasma is transported away from the Io torus has been an issue of concern for quite some time. Because of the rapidly rotating magnetic field, centrifugal acceleration is likely a primary factor in the outward transport of plasma at Jupiter. Many of the models for plasma transport in the Jovian magnetosphere involve the interchange of magnetic flux tubes first discussed by Gold [1959]. Centrifugally-driven radial diffusion has been addressed by Chen [1977] and has attracted considerable attention since the Voyager flybys. For example, Siscoe and Summers [1981], Richardson and McNutt [1987], and Vasyliunas [1989] discuss an eddy-diffusion model which consists of small-scale motions of neighboring flux tubes which interchange positions; the more heavily loaded flux tubes tend to move outward while the relatively less dense tubes move inward. Another model [Pontius et al., 1986; Pontius and Hill, 1989] includes the transient outward convection of individual flux tubes which retain their identity but are modified as they move outward through less dense plasma. We will not consider here the large-scale convection model related to Jupiter's longitudinally asymmetric magnetic field [c.f. Hill et al., 1981].

The various models, then, suggest that one might find flux tubes of varying mass along a typical spacecraft trajectory in the Jovian magnetosphere. The density structures reported in the present work are, therefore, of interest to the plasma transport issue. The transient convection model would appear to predict isolated flux tubes moving outward through the magnetosphere [e.g. Pontius and Hill, 1989] and these might appear as the rather well-defined features reported herein. In fact, a recent paper [Yang et al., 1992] suggests finger-like structures would be created in the magnetosphere on the basis of simulations of the plasma interchange motions. The eddy-diffusion model is similar to a turbulence process, and may be expected to produce small scale variations (in both spatial and density regimes) as opposed to the well-defined structures reported herein. Richardson and McNutt [1987], for example, have examined the Voyager 1 plasma density measurements using special techniques designed to increase the temporal resolution of the analysis at the expense of complete moment determinations to look for such structures near the Io torus. The density variations reported therein are less than about 10%. Vasyliunas [1989] and Mei and Thorne [1991] argue that the scale sizes involved in the eddy-diffusion models should preclude the detection of substantial density structures, consistent with the Richardson and McNutt observations.

We have attempted to analyze the structures observed at 33 R_J to see how they might be related to plasma interchange motion. The fact that we observe well-defined structures would seem to be inconsistent with the eddy-diffusion model which would predict random, white-noise-like density variations. To investigate the spectrum of the density fluctuations we applied a Fourier transform to the density data provided by the 46-minute interval in Figure 1. The resulting spectrum is shown in Figure 4. The first conclusion which we draw from this spectrum is that there are no significant peaks or breaks in the spectrum, particularly at small scale sizes (high frequencies). If the density variations are due to the eddy-diffusion model, one would expect the variations to have small scale sizes. Further, the spectrum is well represented by the line sketched in Figure 4 with a slope of f^{-1}. This is not as steep as a Kolmogorov $f^{-5/3}$ spectrum which would suggest a fully-developed turbulent process. One could envision that eddy-diffusion is initiated at or just outside of the Io torus and the plasma is nearly fully turbulent by the time it arrives at our observing location at 33 R_J.

However, we believe the density fluctuations shown in Figure 2 are not representative of a well-developed turbulent process but rather are well-defined, discrete structures.

The f^{-1} spectrum is what one would expect from the Fourier transform of a series of square wave-like functions. Since the Fourier transform of a square wave is a function proportional to f^{-1}, the linearity property of Fourier transforms assures that the transform of the superposition of many square waves should also be proportional to f^{-1}, at least at frequencies above the shortest period square wave. The discrete flux tubes suggested by the lower panel of Figure 2 seem consistent with the types of structures suggested by Pontius and Hill [1989] or the "fingers" which developed in the simulations of Yang et al. [1992]. We hasten to add, however, that the observed density structures could be produced by a variety of three-dimensional forms and the observation of discrete structures does not uniquely identify either the Yang et al. fingers or the flux tube-like structures predicted by Pontius and Hill [1989]. However, it would seem the observed structures are more consistent with a transient convection model than an eddy-diffusion process.

The density variations are provided by the motion of structures past a single observer and, hence, it is not possible to deduce a three-dimensional form for the structures on the basis of the density observations. Are the structures simple flux tubes of circular or elliptical cross section as predicted by Pontius and Hill [1989]? Are they onion-skin variations organized by L-shell? Are they evidence of the Yang et al. [1992] fingers? Could they be evidence of compressional MHD waves in the plasma sheet? It may be possible to incorporate the magnetic field variations shown in Figure 3 and make greater progress in this area, but a detailed analysis of this nature is beyond the scope of this initial report. However, it is clear by the generally monotonic change in the radial component of the field B_r that wave-like motions of the plasma sheet are not a likely explanation. The cursory discussion of the field variations in the previous section suggested the structures might resemble flux tubes under the influence of centrifugal acceleration.

By examining the cutoff of trapped continuum radiation, the electron density in the Jovian plasma sheet can be determined with good accuracy and with almost arbitrarily high temporal resolution. Using 4-second temporal resolution measurements, we show fully resolved density structures ranging in size from 0.1 R_J to more than an R_J which have plasma density variations of order 2 and scale lengths for density gradients of a few ion Larmor radii. These observations are exemplary of the capabilities of the continuum radiation cutoff method of determining plasma density and show a new type of magnetospheric structure to be explored. We have briefly examined the structures in the context of centrifugally-driven plasma transport models. We conclude that the density structures observed are not likely the result of a well-developed turbulence process, perhaps one similar to the eddy-diffusion model, but the structures are reminiscent of the structures predicted by Pontius and Hill [1989] and Yang et al. [1992] from the transient convection model.

Acknowledgments. This work was begun prior to the tragic shootings at the University of Iowa which took the lives of several of our friends and colleagues, including C. K. Goertz. While he was not able to see this work through to its completion, we are thankful to have had his guidance and support in the early stages of this research. We greatly appreciate useful discussions with Y. S. Yang and R. A. Wolf.

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