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THE STRUCTURE OF THE JOVIAN MAGNETOTAIL FROM PLASMA WAVE OBSERVATIONS

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Abstract. Plasma wave measurements from the outbound passes of Voyager 1 and 2 are used to study the plasma density and structure of the Jovian magnetotail. Two principal types of plasma waves are observed in the magnetotail, continuum radiation and narrowband emissions near the electron gyrofrequency. The low frequency cutoff of the continuum radiation can be used to determine the local electron density. Profiles of the electron density from the outbound passes of Voyager 1 and 2 provide evidence of a broad region of nearly uniform plasma density between the magnetopause and the inner corotating portion of the magnetosphere. We refer to this region as the boundary layer. Comparisons are made with other experimental and theoretical evidence for the existence of such a boundary layer inside the Jovian magnetosphere.

Introduction

The Voyager 1 and 2 spacecraft, which flew by Jupiter on March 5 and July 9, 1979, provided the first measurements of low frequency (10 Hz to 56 KHz) plasma waves in the magnetosphere of Jupiter. During the outbound passes both spacecraft provided an extended series of observations in the downstream predawn region of the Jovian magnetotail. Since insufficient data were available for a full investigation of the magnetotail at the time of first publication [*Scarf et al.*, 1979; *Gurnett et al.*, 1979] we hereby present an analysis of the plasma waves observed during the Voyager 1 and 2 passes through this very interesting region. The spacecraft trajectories in the vicinity of Jupiter are shown in Figure 1, projected onto the orbital plane of Jupiter with the X-axis pointing toward the sun. The local times of the outbound passes are approximately 4.1 and 2.5 hours, respectively. In both cases the outbound trajectories are slightly above the equatorial plane, at latitudes of about 4.9° and 4.1°, respectively. Because of the ~10° tilt of the magnetic dipole axis of Jupiter [*Smith et al*, 1976], coverage is obtained over a range of magnetic latitudes from about +15° to -6° in the outer magnetosphere. As can be seen from Figure 1, the Voyager trajectories provide an excellent survey of the predawn magnetosphere, with the Voyager 2 flyby providing the best measurements to date of the downstream tail region of the magnetosphere. Magnetic field measurements by Ness et al. [1979a, b] have already demonstrated, for example, that the magnetic field in this region takes on a tail-like configuration beyond about 50 R_J, with the magnetic field vectors aligned approximately parallel to the expected position of the magnetopause and to the plasma sheet.

Observations

To provide a survey of the plasma wave observations obtained in the Jovian magnetotail, the plasma wave electric field intensities are shown in Figures 2 and 3 for the entire outbound Voyager 1 and 2 passes by Jupiter. For a description of the plasma wave instrumentation on Voyager, see Scarf and Gurnett [1977]. The electric field intensities in each channel are on a logarithmic scale with a dynamic range of 100 dB, from about 1 μVm^{-1} to 100 mVm^{-1}. In order to provide a plot over the nearly two week interval required for the entire outbound pass, the individual data points have been averaged over intervals of 576 seconds prior to plotting. The most prominent plasma wave phenomenon evident on these plots is the electromagnetic continuum radiation. This radiation is believed to be produced by either mode conversion from electrostatic waves or by synchrotron radiation from energetic electrons. At frequencies below the solar wind plasma frequency, which is ~3 KHz, the continuum radiation is permanently trapped within the low density cavity of the Jovian magnetosphere at frequencies above the local electron plasma frequency, f_p^-. This radiation appears to be closely analogous to continuum radiation observed in the terrestrial magnetosphere [*Gurnett and Shaw*, 1973; *Gurnett*, 1975]. Since the free space electromagnetic mode has a low frequency cutoff at the electron plasma frequency, $f_p^- = 9\sqrt{n}$ KHz, where n is the electron density in cm^{-3}, the electron density can be determined from the low frequency cutoff of the continuum radiation. The plasma frequency cutoff is shown by the dashed lines in Figures 2 and 3, and the corresponding electron densities are indicated by the scale on the right.

Near the planet a well defined 10 hour rotational modulation of the low frequency cutoff of the continuum radiation is clearly evident, with the cutoff frequency varying from as high as 1.78 kHz to as low as 10 Hz. As discussed by Barbosa et al. [1979] and Gurnett et al. [1979] the regions of high cutoff frequency, indicated by the inverted u-shaped lines in Figures 2 and 3 correspond to encounters with the high density regions of the plasma sheet. The propagation cutoff at the electron plasma frequency effectively blocks the radiation from penetrating into the plasma sheet at all frequencies below the local electron plasma frequency. The maximum electron density in the plasma sheet, as determined from the scale on the right hand side of Figures 2 and 3, is seen to vary from about 1×10^{-3} to 3×10^{-2} cm^{-3}. In the region between encounters with the plasma sheet the cutoff frequencies often drop to extremely low values, sometimes less than 30 Hz, which corresponds to densities less than 10^{-5} cm^{-3}. These extremely low cutoff frequencies, which always occur well northward of the magnetic equator, are believed to represent regions of very low plasma density comparable to the tail lobes of the earth's magnetosphere. Comparisons with the magnetic field measure-

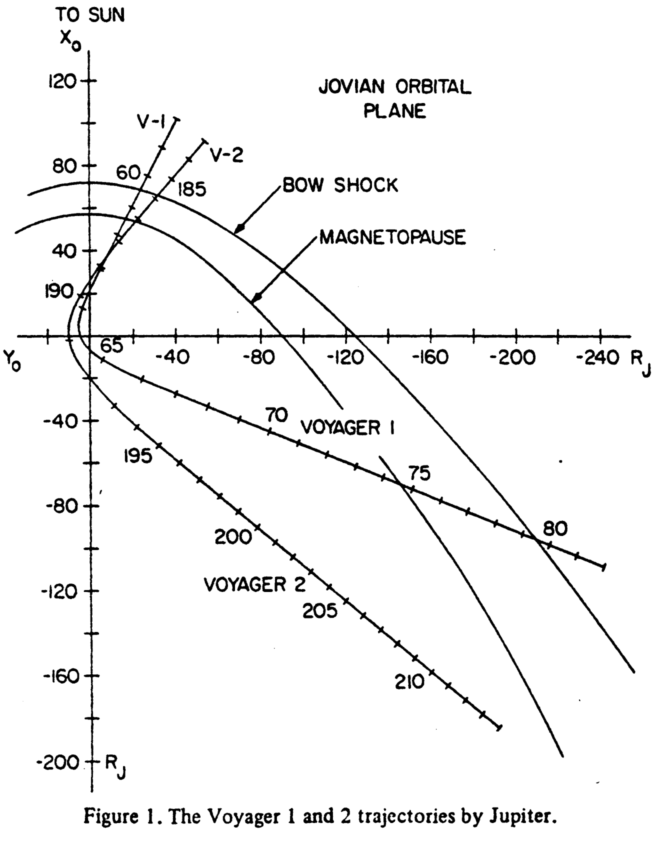

Figure 1. The Voyager 1 and 2 trajectories by Jupiter.

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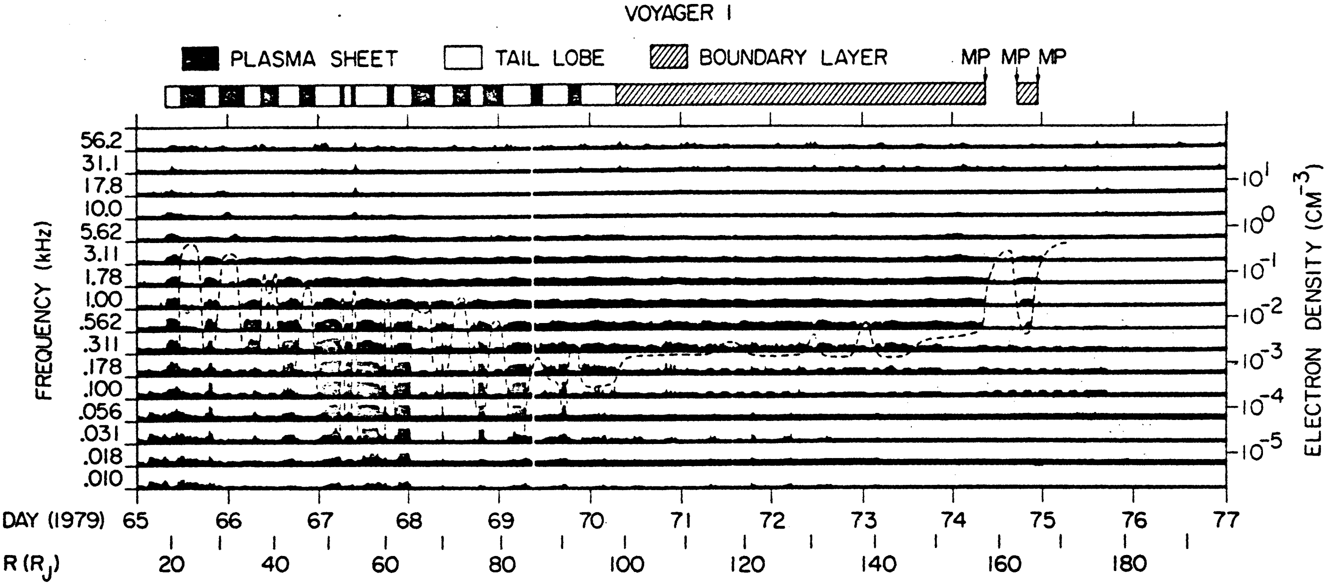

Figure 2. The Voyager 1 plasma wave electric field data from the outbound pass through the magnetotail. The dashed line indicates the electron density profiles obtained from the low frequency cutoff of the continuum radiation.

ments of Ness et al. [1979a, b] confirm that the magnetic field in these regions is relatively strong and steady with a well defined tail-like configuration, as would be expected for the tail lobe region.

The change in the electric field spectrum of the continuum radiation is often quite dramatic from the plasma sheet to the tail lobe regions. Figure 4 shows three representative power flux spectrums, from the tail lobe, from the nightside plasma sheet and from the dayside magnetosphere. Because the slope of the continuum radiation spectrum is very steep, $\sim f^{-4}$, the intensity of the continuum radiation rises very rapidly at low frequencies. For cutoff frequencies less than 100 Hz the continuum radiation frequently reaches broad band intensities of 3 to 5 mVm^{-1}, which are among the highest intensities detected anywhere in the Jovian magnetosphere. Frequently intense narrowband electric field emissions are observed near the electron gyrofrequency in the tail lobe region. An example of this type of emission is shown in Figure 5, which shows an intense narrowband emission at about 800 Hz, slightly below the local electron gyrofrequency, f_g^-. The continuum radiation in this case appears to have a gap or attenuation band on either side of the narrowband feature. Although it is not known for certain whether this narrowband emission is an electrostatic or an electromagnetic wave, it seems most likely that it is electrostatic since somewhat similar narrowband electrostatic waves have also been observed near the electron gyrofrequency in the earth's magnetosphere [*Kennel et al,* 1970].

Based on the continuum radiation cutoff, the regions identified as the plasma sheet and tail lobe are summarized at the top of Figures 2 and 3. The transitions between the plasma sheet and tail lobe show several important features relevant to the structure of the Jovian magnetosphere. Because the magnetic latitude of the spacecraft is biased slightly to the north of the magnetic equator, the latitude usually does not extend sufficiently far south to provide a complete penetration through the plasma sheet into the southern tail lobe. The tail lobe and plasma sheet encounters therefore usually occur only once during each 10 hour rotation of Jupiter. Near the planet, inside of about 60 R_J, the rotational control of the plasma sheet and tail lobe is clearly evident. However, proceeding farther away from the planet the 10 hour periodicity becomes more and more irregular and there is a general tendency to spend more time in the tail lobe. This latter tendency is particularly evident on the Voyager 2 pass. For example, near day 195, from about 60 to 75 R_J, when the 10

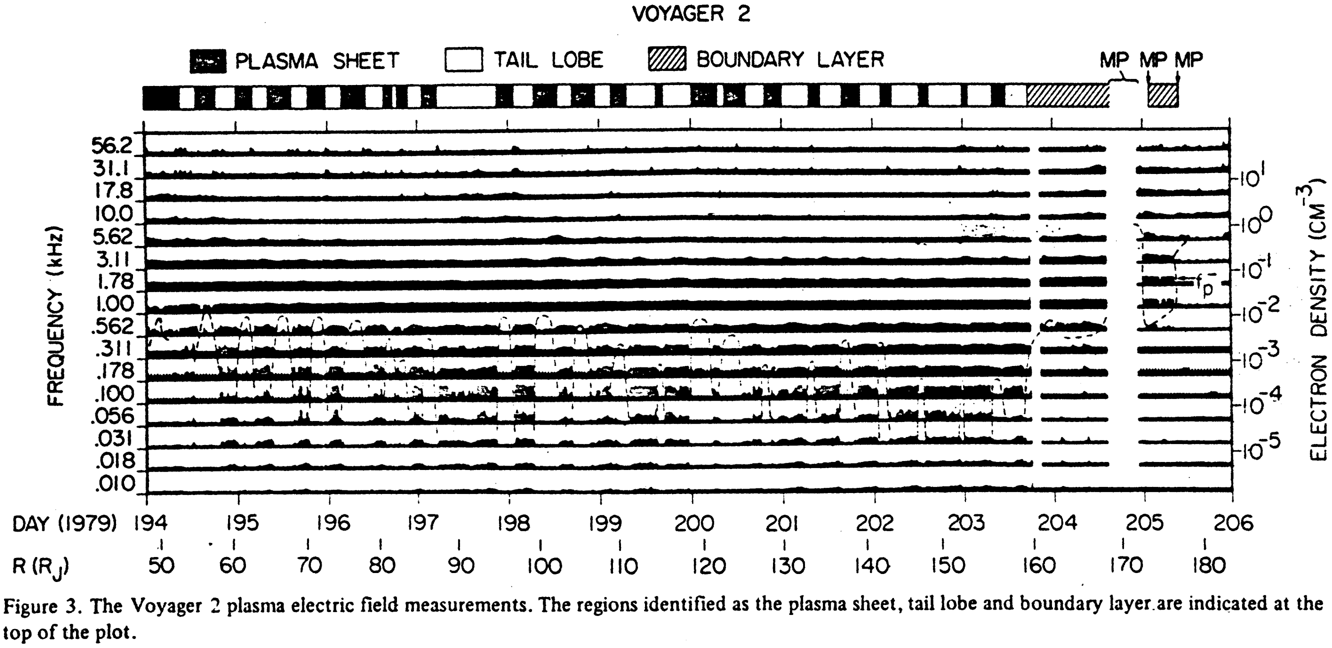

Figure 3. The Voyager 2 plasma electric field measurements. The regions identified as the plasma sheet, tail lobe and boundary layer are indicated at the top of the plot.

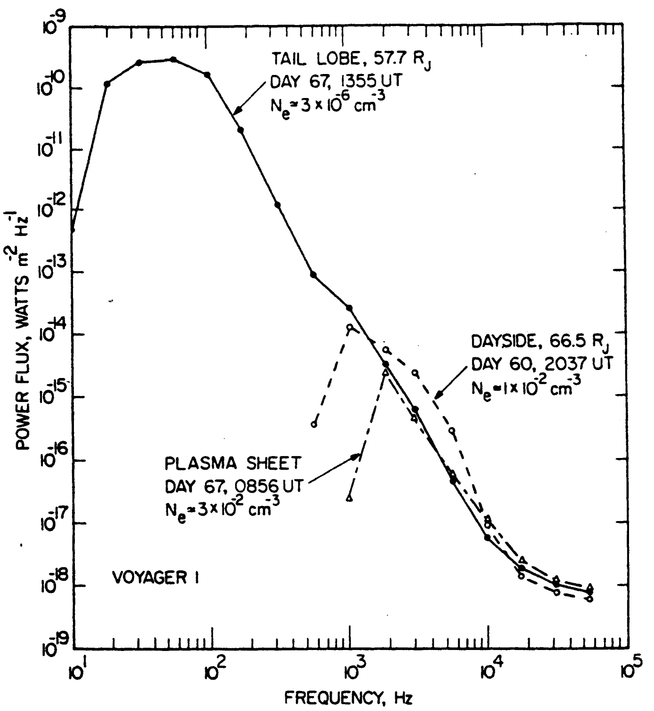

Figure 4. Typical spectrums of the electromagnetic continuum radiation in the nightside plasma sheet, tail lobe and dayside regions of the magnetosphere.

hour periodicity is quite regular the spacecraft is in the tail lobe about half of the time, whereas later, on days 203 to 204, from about 140 to 160 R_J, the spacecraft is in the tail lobe nearly all the time. There is also a general tendency for the electron density in the plasma sheet to decrease with increasing radial distance, as has been previously noted by Barbosa et al. [1979]. Evidence can also be seen at times of major disruptions in the density and apparent thickness of the plasma sheet. For example, on day 68 of Voyager 1, the preceding rather long excursions into the tail lobe are suddenly interrupted and the spacecraft spends most of this day immersed in the plasma sheet. Similarly for the Voyager 2 data, the fraction of the time spent in the tail lobe and in the plasma sheet is seen to fluctuate considerably at various times.

Continuing out to larger radial distances from the planet, a marked transition in the character of the tail lobe/plasma sheet encounters can be seen in the Voyager 1 data at about 0800 UT on day 70 and in the Voyager 2 data at about 1700 UT on day 203. After these times the plasma density remains nearly constant at a relatively high value comparable to the last previous plasma sheet encounter, with no further encounters of the tail lobe even though the spacecraft is scanning a 20° range of latitude once during each rotation of Jupiter. This region of nearly constant density continues until the spacecraft reaches the magnetopause (MP) at about 0900 UT on day 74 for Voyager 1, and at about 2000 ± 0400 UT (in the data gap) on day 204 for Voyager 2. The absence of tail lobe encounters in this region indicates a drastic increase in the north-south thickness of the plasma sheet, from only a few degrees in latitude inside this boundary, to greater than 20° outside. Since this broad region of nearly uniform plasma is located between the inner rotationally dominated region of the magnetosphere and the magnetopause, we shall refer to this region as the boundary layer. For reference, the region which we identify as the boundary layer is indicated at the top of Figures 2 and 3. For the Voyager 1 pass the boundary layer was encountered at about 99.6 R_J and for Voyager 2 the boundary layer was encountered at about 159.2 R_J.

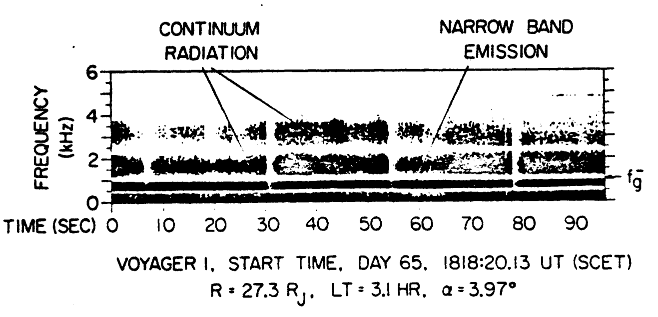

Figure 5. An example of the intense narrowband electric field emissions near the electron gyrofrequency, f_g^-, observed in the low density tail lobe regions.

The results of this study of the structure of the Jovian magnetotail are summarized in Figure 6. Since all of the available measurements are confined to the vicinity of the equatorial plane, the extent to which we can determine the three-dimensional structure out of the equatorial plane is quite limited. The plasma sheet and boundary layer are shown as two distinctly different regions, however, it is likely that the plasmas in these two regions are very closely related since the densities are quite comparable. The principal observational characteristic is that the north-south thickness of the plasma sheet expands very abruptly at the inner edge of the boundary layer. We have also searched for evidence of a similar boundary layer on the dayside of the magnetopause, however, no comparable boundary can be clearly identified in the plasma wave data. The absence of a well defined boundary layer on the dayside of the magnetosphere may however be because the spacecraft latitude never extends sufficiently far from the equatorial region to provide an entry into a low density region comparable to the tail lobe.

Discussion

The Voyager plasma wave measurements show that the dominant plasma wave emissions in the Jovian magnetotail are continuum radiation and a narrowband emission near the electron gyrofrequency. The spectrum of the continuum radiation is extremely steep, $\sim f^{-4}$, and except for the low frequency cutoff at the electron plasma frequency appears to be essentially the same in all regions of the magnetosphere. The close similarity of the spectrum in widely separated regions of the magnetosphere is consistent with the interpretation that the continuum radiation is trapped in the low density magnetospheric cavity at frequencies below the solar wind plasma frequency. As discussed by Gurnett et al. [1979] the most likely source of the continuum radiation is mode conversion from electrostatic waves near the upper hybrid resonance frequency. In regions of extremely low density the continuum radiation often becomes

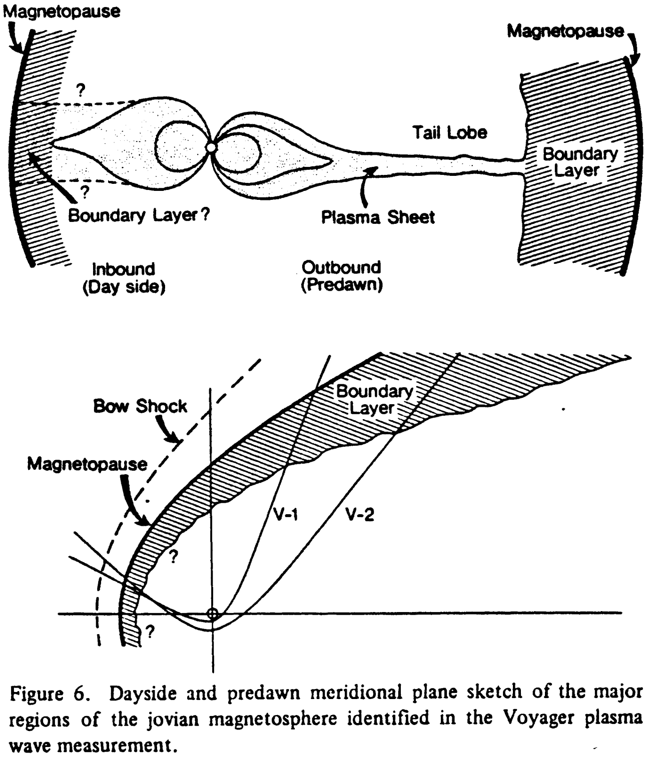

Figure 6. Dayside and predawn meridional plane sketch of the major regions of the jovian magnetosphere identified in the Voyager plasma wave measurement.

very intense, and is one of the most intense plasma wave emissions in the magnetosphere, with broadband intensities of up to 3 to 5 mVm^{-1}. Intense narrowband emissions near the electron gyrofrequency are also observed in these same regions. The mechanisms by which these narrowband waves are generated, and why they only occur in the very low density region outside of the plasma sheet are not understood and need further study. Their occurrence in the same region as the intense low frequency continuum radiation suggests that these waves may be involved in generating the continuum radiation.

Plasma density profiles obtained using the low frequency cutoff of the continuum radiation have revealed new details of the structure of the Jovian magnetotail. The most important features are the observation of the extremely low density, 10^{-5} to 10^{-6} electrons cm^{-3}, region outside of the plasma sheet which we identify as the tail lobe, and the identification of a relatively broad region of uniform plasma density between the magnetopause and the inner corotating portion of the magnetosphere which we refer to as the boundary layer. Comparisons with the results of Ness et al. [1979b] and Krimigis et al. [1979] show that the entry into the boundary layer, at 1700 UT on day 203 for Voyager 2, for example, corresponds to a transition from a relatively well ordered tail-like magnetic field to a region of disordered field, and from a corotating plasma flow to a region of high velocity tailward flow. Krimigis et al. [1979] refer to this later region as the magnetospheric wind.

Evidence has been presented previously, both on experimental and theoretical grounds, for the existence of a boundary layer region inside the Jovian magnetosphere with characteristics similar to that observed by Voyager 1 and 2. In the early Pioneer 10 and 11 results of Van Allen et al. [1974] and Smith et al. [1975] indications are presented of a separate boundary near the magnetopause in which the 10 hour rotational modulation by Jupiter is almost completely absent. Kivelson [1976] further showed that the magnetic field within this layer is highly turbulent, with fluctuations on time scales as short as a few seconds. Theoretical analyses based on a centrifugally driven radial outflow model of the type discussed by Michel and Sturrock [1974] and others, have led to some very specific ideas on why such a boundary layer should exist. As discussed by Kennel and Coroniti [1979], the outflowing plasma from the plasma disk is expected to undergo a shock transition as it approaches the magnetopause, forming an internal boundary layer which is swept downstream from the stagnation point by the interaction with the solar wind. This boundary layer, which they call the planetary wind magnetosheath, should be highly turbulent and should extend completely around the planet if the outflow is super-Alfvenic and only through the nightside regions if the dayside flow is sub-Alfvenic. Our observations of a turbulent boundary layer region in the predawn region are in substantial agreement with these theoretical expectations. It is not clear, however, whether an internal shock is present at the inner edge of the boundary layer. We have examined the plasma wave data for evidence of a shock in this region with inconclusive results. Comparisons with other instruments are needed to determine whether a shock exists at this boundary.

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