Wave Properties Near the Subsolar Magnetopause:  
Pc 1 Waves in the Sheath Transition Layer

P. SONG AND C. T. RUSSELL

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

C. Y. HUANG

Department of Physics and Astronomy, University of Iowa, Iowa City

We study the waves in the frequency range of Pc 1 in the sheath transition layer of the magnetopause from the ISEE 1 and 2 observations. The waves are enhanced in the sheath transition layer, although they are scattered into the magnetosheath when the outer edge of the sheath transition layer is not sharp. A statistical study of 16 cases shows that the wave frequency is proportional to and equal to about 44% of the ion gyrofrequency. The wave amplitude is much greater when the interplanetary magnetic field (IMF) is southward than when the IMF is northward. The waves are left-handed polarized when the IMF is southward but are linearly polarized for northward IMF. The direction of maximum variation is perpendicular to both the background field and the gradients of the field and density when the IMF is northward. For southward IMF, the waves are more turbulent. The wave generation mechanisms apparently depend on the IMF orientations rather than the shock geometry. To investigate the free energy to generate the waves for northward IMF, a method is developed combining the measurements from the fast plasma experiment and Lepeda to obtain a high time resolution estimate of the temperature anisotropy when the IMF is strongly northward. The estimated ion temperature anisotropy is enhanced, up to a factor of 2, within the sheath transition layer for northward IMF.

1. INTRODUCTION

The sheath transition layer is the field transition from the magnetosheath field to the magnetospheric field. There are usually sharp field changes at edges of the sheath transition layer [Russell and Elphic, 1978; Sonnerup et al., 1987; Song et al., 1990a, b], see Figure 1 for example. Thus the magnetopause current can be divided into two parts, one is the sheath transition layer itself and the other is the edges of the sheath transition layer. For strongly northward interplanetary magnetic field (IMF), the inner edge of the sheath transition layer is usually clearly associated with changes in plasma parameters. For strongly southward IMF, usually both edges are very sharp, but the field change within the sheath transition layer may not be as dramatic as that at the edges. Since the magnetopause is in motion with a speed from 10 to 45 km/s [Berchem and Russell, 1982], the edges and the sheath transition layer usually cannot be well resolved. In this study, we choose ISEE 1 and 2 magnetopause crossings when the boundary moves slowly relative to the spacecraft so that we can study the properties of the sheath transition layer. Berchem and Russell [1982] have found the sheath transition layer to be many ion gyroradii thick. Although we still do not know exactly the physical processes within the sheath transition layer, an interesting question is what maintains the thickness of the sheath transition layer.

The ion gyrofrequency near the magnetopause is about 1 Hz which is in the Pc 1 frequency range. Waves near 1 Hz in the vicinity of the magnetopause have been reported by many authors [Cummings and Coleman, 1968; Neugebauer et al., 1974; Fairfield, 1976; Anderson et al., 1982]. Song et al. [1990a] recently reported one slow magnetopause crossing at the subsolar point when the IMF was strongly northward. They found that waves in the Pc 1 frequency range are enhanced within the sheath transition layer. This indicates that the waves are generated within the sheath transition layer. Thus the free energy which generates these waves must be associated with the changes in the plasma and field within this region. The waves may be different for different free energy sources, although they may have similar frequencies. The IMF orientation may be the most important parameter controlling the various waves. When the IMF is strongly southward, there is a large shear in the magnetic field across the layer, the waves may be generated by a current-driven mechanism. When the IMF is strongly northward, the field shear is small and the current is weak. When Song et al. [1990a] reported their case, the gradients in the field and density are the most obvious free energy source. However, using the measured values, the free energy associated with only the field and plasma gradients seems not to be great enough to generate the observed waves, and the temperature anisotropy, the measurements of which were not available at that time with a sufficient high time resolution from ISEE, may be another free energy source for the waves (L. Chen and S. P. Gary, private communication, 1989). In order to address this question Song [1991] developed a technique to estimate the temperature anisotropy with a high time resolution from ISEE 1 measurements. The results showed that the temperature anisotropy is higher within the sheath transition layer than in the magnetosheath. Anderson

Copyright 1993 by the American Geophysical Union.
et al. [1991] recently reported one magnetopause crossing from AMPTE/CCE. These results are consistent with most of the findings of Song et al. [1990a] and Song [1991]. They found the wave enhancements in the Pc 1 frequency range and an enhancement in the temperature anisotropy within the sheath transition layer. Furthermore, they noted that in their case there is a trough in the power spectrum near the gyrofrequency of He++. They interpreted the waves to be ion cyclotron waves even though the waves containing most of energy were linearly polarized and strongly oblique. Traditionally, the term "ion cyclotron wave" is reserved for waves that are left-handed polarized and propagate mainly along the field because electromagnetic ion cyclotron instability typically has a maximum growth rate at propagation parallel to the magnetic field, for which propagation they are left-hand circularly polarized.

In section 2, we show examples of such Pc 1 waves in the sheath transition layer for both strongly northward IMF and strongly southward IMF. In section 3, we show the statistics of these waves. In section 4, to find the possible sources of the free energy for these waves, we show a unique method to estimate the ion temperature anisotropy when the IMF is nearly in the north-south direction by combining the measurements from the fast plasma experiment (FPE) [Bame et al., 1978] and the low-energy proton and electron differential energy analyzers (Lopedea) [Frank et al., 1978]. For a more detailed account of this work and associated studies, see Song [1991].

2. Pc 1 WAVES IN THE SHEATH TRANSITION LAYER

The amplitude of Pc 1 waves in the sheath transition layer is almost always at significant levels, usually above that in the magnetosheath and much above the level in the magnetosphere. In this section we examine the properties of these waves observed on several passes through the magnetopause. To display these data, we use boundary normal coordinates
[Russell and Elphic, 1978]. The N direction is along the normal, the L direction is along the boundary and the tangential component of the magnetospheric field, and the M direction, N x L, completes the system. As can be seen in the examples shown below, the L direction is usually close to the direction of the magnetic field in both the magnetosheath and magnetosphere when the IMF is either strongly northward or southward. Thus the coordinate system is close to field aligned except for a small region where the IMF is strongly southward. The advantage of using the boundary normal coordinates is that the frame is fixed and the field shear which is a source of free energy for the waves can be easily discerned. In the presence of significant wave amplitudes, there may be a large uncertainty in determining the normal direction with the minimum variance technique. For example, if the perturbed field associated with the waves is along the normal direction and the field shear is small, or the major change is in the magnitude, the minimum variance direction will not be the normal direction. In our study, we lowpass filter the resonant waves within the boundary, then perform the minimum variance analysis, and use the tangential discontinuity analysis when applicable.

Figure 1 shows the measurements from the fast plasma experiment [Bame et al., 1978] and the fluxgate magnetometer [Russell, 1978] for a slow magnetopause crossing when the IMF was strongly southward. This crossing occurred at (6.8, -1.6, -0.1)R_E GSM. The IMF measured from ISEE 3 corresponding to the crossing is (1.76, 3.01, -13.26)nT GSM. There are sharp changes in the field and plasma parameters at the edges of the shear transition layer. The magnetopause current is composed of the shear transition layer and its edges. The magnetic field rotates 180° across the magnetopause. However, there is little flow enhancement throughout the crossing. This is different from the prediction of Petschek-type reconnection. Since the FPE measures particles within ±55° of the plane perpendicular to the spin axis, which is along the magnetosheath and magnetospheric fields in this case, it is possible that the flow is along the magnetosheath and magnetospheric fields and is not measured by the FPE. In section 4, we will use Lepedea data to show that there is no flow enhancement along the field at this time. Within the shear transition layer, the field changes its direction relatively gradually with strong fluctuations. This study focuses on these field fluctuations.

Figure 2 shows the power spectra of the magnetic field within the shear transition layer. In the shear transition layer, wave activity is enhanced in a broad frequency range over the magnetosheath level. We are particularly interested in the waves in the Pc 1 frequency range. The center frequency of these waves, at which the wave contains most energy, is 0.52 Hz as indicated by f_o in Figure 2a. The average field in this region is 57.1 nT corresponding to a proton gyrofrequency of 0.87 Hz. Figure 2b shows the details of the spectrum normalized by the proton gyrofrequency. Because of the fluctuations in the magnitude of the field within the shear transition layer, the gyrofrequency also varies. The standard deviation of the gyrofrequency here is 6%. The amplitudes of the waves are similar for the three components, and the spectra are broad rather than peaked. Figure 2b also shows the polarization as a function of frequency. Here, we define right-hand waves to be those with ellipticity from 0.33 to 1 (hatched bar), linearly polarized waves as those from -0.33 to 0.33 (open bar), and left-hand waves from -1 to -0.33 (solid bar). The waves with most of the power are left-handed polarized. The frequency at which the wave changes from left-hand to right-hand can be used to estimate the Doppler-shift of the ion gyrofrequency. In the plasma frame, the left-hand wave does not exist at frequencies above the ion gyrofrequency to a portion of the plasma frequency. Therefore, we believe that the frequency at which the polarization changes should be near the Doppler-shifted ion gyrofrequency. The difference between this frequency and the ion gyrofrequency gives the Doppler shift frequency for the wave near the ion gyrofrequency. This estimate may slightly underestimate the magnitude of the Doppler shift near the ion gyrofrequency. Since the wave of most energy may have a different wave vector, both in
direction and in magnitude, its Doppler shift may be different from that near the ion gyrofrequency. For this crossing, the estimated Doppler shift is about $0.15 f_{\text{cr}}$.

To identify the source region of the wave, we can examine the amplitude of the wave as a function of position. In general, the amplitude of an MHD wave should decrease away from the source region if the phase velocity does not increase significantly. Figure 3 shows the high-pass filtered magnetic field data. The bottom panel shows the magnetic field strength for reference. The lower cutoff frequency of the filter was chosen to be 0.4 Hz. The Nyquist frequency for our data is 2 Hz. Since this frequency range includes most of the wave power, the profile of the plot will not be changed by selecting a slightly smaller lower cutoff frequency. It is obvious that the waves are enhanced in the transition layer. It is possible that the enhancement of the waves in the sheath transition layer is due to changes in plasma parameters and not due to the generation of the waves. Let us assume the waves are generated upstream of the sheath transition layer, but no more free energy is added to the waves in propagation. Because the wave energy flux is conserved across a plane parallel to the transition layer, the wave energy $\delta B^2/2 \rho_v$ is anticorrelated.

Fig. 4. Power spectra of the waves in the sheath transition layer on September 13, 1980, in the same format as Figure 2. The spectrum of the magnetosheath is for 4 min intervals started at 0641 UT.
with the phase velocity of the waves normal to the plane. We recall for a cold plasma in the low-frequency limit the phase velocity is the Alfvén velocity along the field and is the magnetosonic velocity across the field. To lowest order, the phase velocity is proportional to the Alfvén velocity. Thus the wave energy is anticorrelated with the Alfvén velocity. From the magnetosheath to the sheath transition layer the Alfvén velocity decreases 70%, which would lead to only a 35% increase in the wave amplitude. Therefore, the enhancement of the waves in the sheath transition layer cannot be explained by propagation of the magnetosheath waves into this region. The waves must be generated within the sheath transition layer. The amplitude of the waves in the sheath transition layer is 9.3 nT. The amplitude of the wave is defined as \((2\alpha_1)^{1/2}\), where \(\sigma_1\) is the maximum variance, or the standard deviation. These waves are left-handed polarized with a compressional component.

Figures 4 and 5 show the power spectra, polarization, and filtered magnetic field data for another slow magnetopause crossing on September 13, 1980, when the IMF was strongly southward, (-0.29, 4.65, -7.05)nT GSM measured by IMP 8. The lower cutoff frequency for the filtering is 0.12 Hz. The crossing occurred at \((10.0, 0.1, 2.8)R_E\) GSM. Plasma measurements are not available for this crossing. The wave is enhanced in the sheath transition layer, and the wave properties are similar to those in the first crossing. The estimated Doppler shift is about 0.55 \(f_r\).

Figure 6 shows the plasma and field measurements for a slow magnetopause crossing when the IMF was strongly northward. The IMF measured by IMP 8 corresponding to the crossing is \((3.64, -1.13, 2.60)\)nT GSM. This crossing occurred at \((9.5, -5.9, 5.0)R_E\) GSM. In this crossing, the magnetic fields on both sides of the magnetopause are essentially parallel. In the sheath transition layer, the field increases in magnitude from the magnetosheath as the plasma density decreases. The plasma in this region is depleted magnetosheath plasma. Figures 7 and 8 show the power spectra, polarization, and filtered magnetic field data. The wave in the sheath transition layer for this northward IMF crossing is enhanced only in the \(P_c 1\) range, one of the major differences from the southward IMF crossing. The left-hand/right-hand turning frequency is at 1.5 \(f_r\). Thus, the estimated Doppler shift for the wave near the ion gyrofrequency is about 0.5 \(f_r\). The lower cutoff frequency for the filter is 0.1 Hz. The waves are transverse and are concentrated in the sheath transition layer. Therefore the waves are generated within the transition layer. The power and the amplitude of the waves in this crossing are much smaller than that in the two southward IMF crossings shown earlier. Another difference from the southward IMF crossings is that the power for the two transverse components is higher than the compressional component for the frequency range of interest. The waves are near linearly polarized rather than nearly circular as in the previous two cases. Figures 9, 10, and 11 show the plasma and field measurements for another northward IMF crossing near the subsonar region \((10.4, -1.1, 5.2)R_E\) GSM. This crossing has been studied by Paschmann et al. [1978], Russell and Elphic [1978] and Parks et al. [1978]. The sheath transition layer was called the depletion layer by Paschmann et al. and the magnetopause current layer by Russell and Elphic. We now would call the inner edge of the layer the "magnetopause" in a narrow sense. Since this "depletion" layer
Fig. 6. Measurements for a slow magnetopause crossing by ISEE 1 (solid lines) and ISEE 2 (dashed lines) on Nov. 24, 1977, in the same format as Figure 1. The locations of this crossing is at (9.5, -5.9, 5.0)R\_GSM. The normal vector is (0.781, -0.423, 0.459) GSE and determined by the tangential discontinuity analysis from ISEE 1.

Fig. 7. Power spectra of the waves in the sheath transition layer on November 24, 1977 in the same format as Figure 2. The magnetosheath spectrum is for 4 min intervals started at 1926 UT.
does not show plasma depletion for southward IMF cases as shown in Figure 1, we call it the sheath transition layer to distinguish it from "the magnetopause" and to describe more general situations. Being similar to the last crossing, the sheath transition layer contains gradual changes in the field strength and plasma density. However, for this crossing, since the changes at the outer edge of the sheath transition layer are weak, the waves are not well confined in the sheath transition layer, but the properties of the waves are similar to the last crossing. The overall structure and properties of these two northward IMF crossings are similar to the crossing reported by Song et al. [1990a]. The left-hand/right-hand turning frequency is at 1.1 $f_o$. Thus the estimated Doppler shift for this crossing is small.

3. STATISTICS

We have looked through the ISEE 1 and 2 magnetopause crossings searching for slow crossings near the subsolar region during which the sheath transition layer can be resolved from its edges. We have found 16 such crossings. Since the nature of the waves is determined by the free energy that generates these waves, it may depend on the orientation of the IMF. When the IMF is strongly northward, there is little field shear across the magnetopause. The free energy associated with the field shear or the current may not be dominant. However, when the IMF is strongly southward, the major free energy source is the current. In this study, the IMF orientation is determined by either ISEE 3 or IMP 8, shifted according to the time delay, when the IMF data are available. When the IMF data are not available, the magnetosheath field orientation is used. We divide the crossings into three categories, strongly northward, strongly southward and horizontal IMF. Most of our slow crossings were obtained when the IMF was strongly northward because the magnetopause is less oscillatory for northward IMF [Song et al. 1988]. We find significant wave amplitudes near the Pc 1 range for all of the crossings. Figure 12 shows the dependence of the amplitude of the waves on the background field strength averaged over the sheath transition layer. In general, the amplitude of the waves is greater for strongly southward IMF crossings and is smaller for strongly northward IMF crossings. The amplitude of the waves for northward IMF crossings seems proportional to the background field strength. The normalized wave amplitude $\Delta B/B_o$ is 5.3% from the best fit for the northward IMF crossings. Figure 13 shows the central frequency of the waves versus the background field strength. The central frequency is the frequency containing most wave energy, and it is near the peaks near the kink point in the spectrum of the component with the greatest power. There is a clear linear relation between the field strength and central frequency regardless of the IMF orientation. The best linear fit indicates the frequency is typically 0.44 $f_o$.

As shown in the examples, the estimated Doppler shift for the wave near the proton gyrofrequency is up to 50%. As discussed earlier, the actual Doppler shift for the wave with most of the energy may be different from that determined by the left-hand/right-hand turning frequency. However, because the Doppler shift may either increase or decrease the phase velocity in the spacecraft frame, the observed frequency may either be greater or less than the frequency in the plasma frame. Hence the average measured frequency may be a good estimate of the frequency in the plasma frame, and the fluctuations in the measured frequency around the average frequency may be associated with the Doppler shift. A case studied by Song et al. [1990a] has the least flow effect and gives a measured frequency of 0.5 $f_o$. In any circumstances, the observed relationship indicates that these waves are associated with the ion gyromotions.
Fig. 9. Measurements for a slow magnetopause crossing by ISEE 1 on November 5, 1977, in the same format as Figure 1. The location of this crossing is at (10.3, -1.1, 5.1)R_e GSM. The normal vector is (0.835, -0.190, 0.516) GSE and determined by the tangential discontinuity analysis from ISEE 1.

Fig. 10. Power spectra of the waves in the sheath transition layer on November 5, 1977 in the same format as figure 2. The 4 min interval for the magnetosheath spectrum starts at 1640 UT.
Fig. 11. High-pass filtered magnetic field data on November 5, 1977, when the IMF was strongly northward. Although the waves are strong in the sheath transition layer and weak in the boundary layer and magnetosphere, they also occur in the magnetosheath.

Fig. 12. Wave amplitude versus background field. The amplitude is larger for southward IMF.

Fig. 13. Wave frequency versus background field.

The wave properties of the 16 crossings are listed in Table 1. $B_0$ is the background field averaged over the sheath transition layer. The amplitude of the wave is $\delta B$ and is $\sqrt{2}$ times the standard deviation of the fluctuations. Plasma beta is measured in the wave region. The wave frequency $f$ is the frequency containing most energy, or the frequency of maximum in power times frequency. The ellipticity is the ratio of the wave amplitude in the intermediate eigenvector direction to that in the maximum eigenvector direction in the bandwidth of the wave when its absolute value is smaller than 0.5, and is the same but measured in the plane perpendicular to the wave vector as defined by the imaginary part of the cross-spectral matrix when its absolute value is greater than 0.5. For most of the crossings, the compressional component of the waves is small. The waves for most of northward IMF crossings are linearly polarized. However, the waves for southward IMF crossings are predominantly left-handed polarized. Note that the direction of maximum variation is not well determined for larger absolute values of the ellipticity and that the direction of minimum variation is not well determined for smaller absolute values of the ellipticity. For most of the northward IMF crossings, the direction of maximum variation is the $M$ direction, which is perpendicular to both the magnetospheric field and the gradients of the density and field, and the direction of minimum variation is the $L$ direction, which is the direction of the magnetospheric field. For southward IMF
crossings, there seems no good order in the direction of either maximum or minimum variation, perhaps due to the small number of the examples.

The ratio of the minimum eigenvalue $\sigma_2$ and the maximum eigenvalue $\sigma_1$ is a measure of the degree of turbulence of the waves. From Table 1, there is a tendency for an increase in the ratio of the two eigenvalues from northward IMF to southward IMF. For the three southward IMF crossings $\sigma_2/\sigma_1$ is larger than 20%. The average of $\sigma_2/\sigma_1$ for the 11 northward IMF crossings is 12%. Therefore, the field variations are somewhat more turbulent for southward IMF crossings.

Although it is clear that for most of cases, the waves in Pc 1 frequency range are enhanced in the sheath transition layer, indicating that the source of the Pc 1 waves is within the sheath transition layer if the waves are damped away from the source region, one may still speculate that the waves are controlled by the upstream magnetosheath conditions. The magnetosheath conditions are most strongly affected by the upstream shock geometry, namely, if the region is downstream of a quasi-perpendicular shock, when the angle between the shock normal and IMF, $\theta_{\text{norm}}$, is between 45° and 135°, or the region is downstream of a quasi-parallel shock, when $\theta_{\text{norm}}$ is between 0° and 45° or between 135° and 180°. Since according to MHD picture, the flow over the entire magnetopause arises along the stagnation streamline, the magnetosheath near the magnetopause is formed by the streamlines from the subsolar region. The shock geometry near the subsolar region is determined by the IMF cone angle $\theta$, the angle between the IMF and the Sun-Earth line. In Table 1, we show the IMF cone angle for the crossings when the IMF measurements are available. The IMF measurements are from either IMP 8 or ISEE 3 with 5-min resolution and are shifted by the time lag between the IMF monitor and ISEE 1 and 2. Of the 11 crossings during which the IMF measurements are available, four crossings are for the quasi-parallel shock and seven crossings are for the quasi-perpendicular shock. Previous observations have shown that the magnetosheath is more turbulent for the quasi-parallel shock [e.g., Engebretson et al., 1991; Lin et al., 1991]. The two southward IMF and the two horizontal IMF cases during which the wave amplitude is greater all occurred for the quasi-perpendicular shock. Thus the greater amplitude of the Pc 1 waves for these cases cannot be due to a more turbulent magnetosheath resulting from the quasi-parallel shock. The two northward IMF cases shown in this paper are one for each shock geometry. There is no apparent difference between the two cases, for example, in the amplitude and ellipticity. This result indicates that the shock geometry does not control the Pc 1 waves in the sheath transition layer, although it may strongly influence the Pc 3-4 waves in the magnetosheath. However, the large amplitude of the waves for the southward IMF cases may be partly affected by the plasma beta. For southward IMF, the magnetic field within the sheath transition layer may be weaker than that in the magnetosheath. Because of the total pressure balance, the thermal pressure and hence the plasma beta are higher in the sheath transition layer. The waves have a larger growth rate for a higher beta plasma [e.g., Gary, 1992] because the field lines in a high beta plasma are less rigid and easier to distort. Therefore the waves are easier to grow to a large amplitude. To check the effect of the plasma beta, we have included the beta, when available, in Table 1. Overall, we see a correlation between beta and wave amplitude, although other mechanisms still are needed to explain the residual differences.

### 4. Ion Anisotropy Measurements

Determining the possible sources of the free energy is the key to understanding how a wave is generated. In section 3, we have shown that the waves are very different in both the amplitude and ellipticity for different IMF orientations. Possible sources of free energy are the gradients in the density and field for northward IMF crossings and the large field shear for southward IMF crossings. As discussed in the introduction, the field shear may be large enough to generate current-driven waves for southward IMF, and the free energy associated with the density and field gradients may not be large enough to generate the waves for northward IMF. Another possible source of free energy is the plasma temperature anisotropy.
For strongly northward or southward IMF, the magnetic field is nearly along the spin axis of the ISEE spacecraft. The two-dimensional FPE measurements cannot sample the direction along the magnetic field so we cannot obtain the temperature anisotropy from the FPE. Plasma measurements in the third direction are available from the Lepeda measurements [Frank et al., 1978]. However, the three-dimensional ion measurements from the Lepeda have very low time resolution, 128 s to make a complete measurement for high bit rate and 512 s for low bit rate. Since a low time resolution average over a short transition is meaningless for studies of small scales, here we present a method combining the low time resolution three-dimensional Lepeda data with the high time resolution two-dimensional FPE data to obtain high time resolution three-dimensional quantities (see Appendix). Although this method is specially designed for ISEE 1 to estimate the temperature anisotropy and other spacecraft may not have the same problem, the principle of this method can be generalized to other situations for other instruments. The two assumptions for this method are (1) the field is nearly along the spacecraft spin axis, or \( B_z \) is the dominant component of the field in spacecraft coordinates; and (2) the distribution function for particles is convective bi-Maxwellian. Under the first assumption, we can measure the fluxes in different directions relative to the field by selecting the measurements from particular detectors and particular directions, while the spacecraft is spinning. In particular, we are interested in the directions along the field and perpendicular to it. The second assumption, convective bi-Maxwellian distribution, is ideally how an anisotropy is calculated. The meanings of the flux ratios between parallel and antiparallel fluxes and between parallel and perpendicular fluxes are illustrated in Figure 14. Figure 14a shows the contours of a convective bi-Maxwellian distribution. Here we have chosen the perpendicular direction as the direction perpendicular to the field and flow. The parallel and antiparallel distributions are shown in Figure 14b. A complete scan of the Lepeda at an energy level takes 16 s and gives a vertical cut on the two distributions. The ratio of parallel and antiparallel fluxes provides information about the field-aligned velocity. The ratio of perpendicular and parallel fluxes, Figure 14c, provides the information about the anisotropy. As the energy level increases, the Lepeda samples the high-energy tail of the distribution. It becomes less sensitive to the bulk distribution or even completely different from the bulk distribution if the high-energy population has different behavior from the low energy population which is dominant in the momentum. Under these two assumptions, the FPE measures the perpendicular temperature \( T_p \) of the bulk population. The ratio of the temperature measured by the FPE and the energy level of the Lepeda for a scan, \( E \), provides a measure of how close the Lepeda is sampling to the bulk in the scan. Thus we can use the flux ratios from the Lepeda to determine the anisotropy and \( z \) component of the velocity for each scan. Two restrictions on this method are the insensitivity at small absolute value of \( T_p/E \) and the appearance of multiple populations. For the first restriction, we find that the calculated anisotropy and \( z \) component of the velocity have clear modulation by the ratio of \( T_p/E \) when the absolute value of \( \ln(T_p/E) \) is larger than unity. Therefore we restrict the calculated quantities for the intervals when the absolute value of \( \ln(T_p/E) \) is smaller than unity. The second restriction may affect the calculated quantities in the magnetosphere where multiple populations may occur; but the flux ratios are still correct and they can be used as an indicator for high-speed flow of reconnection for southward IMF. The finite field angle of the FPE may cause uncertainty in \( T_p \) measurements, but this is a high-order effect.

Figures 15 to 18 show the three-dimensional information reduced by this method for the three magnetopause crossings for strongly northward IMF studied in this paper and by Song et al. [1990a] and the first crossing for strongly southward IMF in this paper. The top four and the bottom panels provide the information of the data reduction. The fifth and sixth panels show the estimated ion temperature anisotropy and \( z \) component of the velocity. For the northward IMF cases, the results are suggestive of a moderate temperature anisotropy increases from the magnetosheath to the sheath transition layer. This is consistent with the measurements from other instruments and spacecraft [Tsurutani et al., 1982, Anderson et al., 1991, also Paschmann, private communication, 1992]. The \( z \) component of the ion velocity is of the same order as the other two components. For southward IMF, this method does not apply within the sheath transition layer, where the field changes its direction significantly and hence is not in south-north direction. From three-dimensional electron and energetic particle measurements, the particles with medium and high energy within the sheath transition layer are quite isotropic and the electrons with low energy are more parallel to the field for southward IMF [Song, 1991], although no ion temperature anisotropy is measured. In the magnetosheath and magnetosphere, the magnitude of the \( z \) component of the ion velocity is similar to those of the other two components. In the sheath transition layer and boundary layer there is no
significant change in the ion flux ratio of \( F_i/F_e \) which is relative to the \( z \) component of the velocity. Thus, for this crossing, there is no flow enhancement as predicted by the Petschek-type reconnection although the magnetic field is antiparallel on the two sides of the magnetopause. This event cannot be explained by the plasma beta effect on reconnection. 

*Paschmann et al.* [1986] have found that for high-speed flow events, the velocity increase within the magnetopause is anticorrelated to the magnetosheath plasma beta. For this crossing, the magnetosheath plasma beta is not large, 0.5, although the plasma beta within the sheath transition layer is much greater, \( \sim 4 \).

5. DISCUSSION

It is clear that the waves in the sheath transition layer for strongly northward IMF are associated with the field and density gradients and ion temperature anisotropy. The waves will consume the free energy. It was first recognized by *Crooker and Siscoe* [1977] that an increase in ion temperature anisotropy may be caused by the plasma depletion effect [*Midgley and Davis*, 1963; *Lees*, 1964; *Zwan and Wolf*, 1976], although the theoretical approaches of the plasma depletion effect assumed the isotropic situation. The magnetic field strength increases due to the depletion effect to maintain the
total pressure balance and in turn the particles will become more perpendicular to the field to conserve the magnetic moment. Moreover, the particles moving along the field are lost more quickly than the particles with larger pitch angles when a flux tube moves toward an obstacle and is bent. There is no wave required for these two processes, but they may generate waves due to the increase in the anisotropy. Further depletion can be performed with help of waves. Waves can scatter particles from perpendicular to the field to along it through pitch angle diffusion [Kennel and Petschek, 1966]. Thus, the Pc 1 waves may be partly due to the depletion and then assist in further depletion. On the other hand, since larger wave amplitude causes stronger pitch angle diffusion, faster depletion and hence a stronger density gradient, the component of the waves due to the gradients becomes more important, and this component of the waves tends to remove the density gradient. Thus, the sheath transition layer for northward IMF may be in a self-balanced situation for these two competing processes. Therefore, these Pc 1 waves may be a key to understanding what maintains the thickness of the magnetopause current layer.

The Pc 1 waves in the sheath transition layer for northward IMF have also been studied by Anderson et al. [1991] using the AMPTE/CCE data. Since the AMPTE/CCE has a different orientation of the spin axis, it can measure the temperature anisotropy for strongly northward IMF with a two-dimensional instrument. Anderson et al. studied one such case and referred to the sheath transition layer as the plasma depletion layer. Consistent with the results of Song [1991] and this paper, they found that the ion temperature anisotropy is enhanced to 2 in
the sheath transition layer. The wave amplitude, frequency, and compressional ratio for their case are within the range of our statistics. They also found the wave spectrum is divided into two branches by the He** gyrofrequency in their case. We have checked our spectral analysis using different selected intervals for each case. We are not able to find a slot at the He** gyrofrequency. One may argue that the change in the polarization near 0.4\(f_\omega\), for the November 5, 1977 case, Figure 10, is consistent with the case of Anderson et al. However, there is no clear slot in the spectra. Also, this is a good example which shows that waves containing the most energy are linearly polarized. Using the portion of the spectra containing almost no energy to identify the wave mode for the whole spectrum is somewhat not convincing. Although Anderson et al. classified their waves as the electromagnetic ion cyclotron waves, as discussed in the introduction, we think that the wave for northward IMF is not a classical mode for homogeneous plasmas and the wave mode due to the gradients plays a significant role in the process.

The Pc 1 waves in the sheath transition layer for southward IMF have been reported recently by Rezeau et al. [1989], Saunders [1989] and Takahashi et al. [1991]. The case shown by Rezeau et al. is similar to our southward IMF cases. The amplitude is 15%, and the ratio of the minimum and maximum eigenvalues is 0.22. However, the waves may be right-handed. They interpreted these waves as small-scale Alfvénic structures. The case shown by Saunders is associated with high speed and is interpreted as due to the Kelvin-Helmholtz instability. There was no detailed spectral and minimum variance analysis reported for his case. We interpret the Pc 1 waves for southward IMF to be ion cyclotron turbulence since the waves are left hand and far from monochromatic. Strong ion heating occurred in this region for the crossing of November 25, 1978 [Song et al., 1990b]. Thus these waves

Fig. 17. Result of combining the Lepedea and FPE measurements on November 24, 1977, in the same format as Figure 15.
Fig. 18. Result of combining the Lepede and FPE measurements on November 25, 1978, in the same format as Figure 15.

may provide a means to convert field energy into particle energy in reconnection processes. Here we want to emphasize that the waves for southward IMF are much more complicated than that for northward IMF. They are enhanced in a much larger frequency range even up to the electron gyrofrequency [Song et al., 1990b], although the wave properties may change with frequency. The waves near the proton gyrofrequency contain the most energy.

6. CONCLUSIONS

We have studied the Pc 1 waves in the sheath transition layer of the magnetopause. These waves appear to be generated within the sheath transition layer. The amplitude of the waves is greater for southward IMF than that for northward IMF. The average frequency of the waves is proportional to the ion gyrofrequency and is about 0.44 $f_g$ on average. For southward IMF, these waves appear to be ion cyclotron turbulence and associated with ion heating. For northward IMF, these waves appear to be linearly polarized with the maximum variation direction perpendicular to both the background field and the direction of the density gradient. There is no evidence that the differences in the waves in Pc 1 frequency range are related to the shock geometry. The wave properties are determined by the condition of the magnetosheath-magnetosphere interaction.

The estimated ion temperature anisotropy derived by combining the FPE and Lepede data indicate that the anisotropy can be as large as 2 for northward IMF crossings. Thus the free energy to generate these waves is the field shear for strongly southward IMF and is the density gradient and ion temperature anisotropy for strongly northward IMF. These waves may be the key to understanding the mechanisms which maintain the thickness of the magnetopause current layer for northward IMF and may provide a means to convert field energy into particle energy for reconnection processes.
APPENDIX

Assume a convective bi-Maxwellian distribution

\[ f = \exp \left[ - \frac{\left( v_x - v_{xo} \right)^2 + v_y^2}{2a_{\perp}^2} - \frac{\left( v_z - v_{zo} \right)^2}{2a_{\parallel}^2} \right] \]  

(A1)

where \( a_{\perp} \) and \( a_{\parallel} \) are the perpendicular and parallel thermal velocities, the magnetic field is in the \( z \) direction, and the bulk velocity is \((V_{xo}, 0, V_{zo})\). The \( x \) direction is the flow direction in the plane perpendicular to the field.

In spherical coordinates (A1) is

\[ f(E, \theta, \phi) = \exp \left[ - \frac{E}{T_{\perp}} \left( \sin^2 \theta - \frac{2V_{zo}}{V} \right) \sin \theta \cos \phi \right. \]

\[ \left. + \frac{V_{zo}^2}{V^2} + A \left( \frac{\cos \theta - V_{zo}}{V} \right)^2 \right] \]  

(A2)

where \( \theta \) and \( \phi \) are the colatitude and azimuthal angles of the coordinates, see Figure A1, \( E = m v^2 / 2 \) is the energy of particles, \( T_{\perp} \) is the temperature perpendicular to the field, and \( A = T_{\parallel} / T_{\perp} \) is the temperature anisotropy.

Near the equator, the magnetic field is essentially along the spin axis of ISEE 1, which is in north-south direction, for strongly northward IMF or for strongly southward IMF except for a small region near the neutral plane. Since the FPE measures the plane perpendicular to the spin axis, the temperature measured is \( T_{\perp} \), and the velocity is in the \( x-y \) plane. We can rotate the coordinates to make our \( x \) axis along the direction of the velocity measured by the FPE. There were seven detectors in different latitudes in the Lepedea. Sensors 1 and 7 are essentially northward and southward, and sensor 4 is in the \( x-y \) plane. The Lepedea samples the azimuthal angles while the spacecraft spins. It samples one energy range in a complete scan then changes to the next energy range. Since detectors 1 and 7 have a smaller geometrical factor and hence a smaller flux than other detectors, we use the measurements from detectors 2 and 6 in our calculation. Let

\[ f_{y\perp}(E) = f(E, \pi / 2, \pi / 2, \pi / 2) \]

\[ \exp \left[ - \frac{E}{T_{\perp}} \left( 1 + \frac{V_{zo}^2}{V^2} + \frac{V_{zo}^2}{V^2} A \right) \right] \]

(A3a)

\[ f_{\parallel}(E, \theta, \phi, \left. \left( \frac{\pi}{2}, \frac{3\pi}{2}, \frac{3\pi}{2} \right) \right) \exp \left[ - \frac{E}{T_{\perp}} \left( \sin^2 \theta_2 + \frac{V_{zo}^2}{V^2} + A \left( \cos \theta_2 - \frac{V_{zo}}{V} \right)^2 \right) \right] \]

(A3b)

\[ f_{z\perp}(E, \theta, \phi, \left. \left( \frac{\pi}{2}, \frac{3\pi}{2}, \frac{3\pi}{2} \right) \right) \exp \left[ - \frac{E}{T_{\perp}} \left( \sin^2 \theta_2 + \frac{V_{zo}^2}{V^2} + A \left( \cos \theta_2 - \frac{V_{zo}}{V} \right)^2 \right) \right] \]

(A3c)

where \( \theta_2 \) and \( \phi_2 \) are the colatitude and azimuthal angles for the detectors 2 and 6.

Since the measured flux is proportional to the distribution function, the three quantities can be measured with the Lepedea by choosing the flux in proper detectors at corresponding azimuths and using the energy of this scan for \( E \).

Solve A3 for \( A \) and \( V_{zo} \) we obtain

\[ A = 1 + \frac{T_{\perp}}{E} \frac{1}{\cos^2 \theta_2} \ln(f_{y\perp} / f_{z\perp}) \]  

(A4)

\[ V_{zo} = \frac{V}{4 \cos^2 \theta_2} \frac{1}{T_{\perp} \ln(f_{y\perp} / f_{z\perp})} \]  

(A5)

where we have assumed \( \theta_2 = 180 - \theta_2 \) or \( \cos \theta_2 = -\cos \theta_2 \).

Since \( T_{\perp} \) can be measured by the FPE with high time resolution and the rest of the quantities on the right-hand side of A4 and A5 can be determined by the Lepedea in each scan, the anisotropy \( A \) and the \( z \) component of flow velocity \( V_{zo} \) can be, in principle, determined for each scan of the Lepedea which takes 16 s and is substantially faster than a complete measurement of the instrument.

In reality, the determination of \( A \) and \( V_{zo} \) in this method depends on the ratio \( T_{\perp}/E \). When this ratio is close to unity, the Lepedea in fact is sampling the bulk of the distribution, and thus this method gives a good determination. When \( E \) is much larger than \( T_{\perp} \), the Lepedea is sampling the high-energy tail of the distribution, and hence this method becomes less sensitive. Therefore, in this paper, we use the determination of \( A \) and \( V_{zo} \) only when \(-1 < \ln(T_{\perp}/E) < 1 \). Because the fluxes in (A4) and
(AS) are all from the Lepedea, the different calibrations of the FPE and Lepedea will effect little on our results.

This method can also be generalized to a Kappa distribution by using a Kappa distribution as the original distribution. However, this method is not useful when particles from different sources have similar importance. In this situation, the flux ratios can still provide some useful information.

Acknowledgments. We wish to thank J. T. Gosling for providing the FPE data and useful discussions. The work at UCLA was supported by a grant from the Institute of Geophysics and Planetary Physics at Los Alamos. The research at the University of Iowa was supported by the National Aeronautics and Space Administration under contract NAGS-28700. We are grateful for the use of the ISEE-1 and 2 FPE data (Principal investigators, S. J. Bame and G. Paschmann, respectively. We also thank the two referees for useful discussions.

The Editor thanks N. Scopke and another referee for their assistance in evaluating this paper.

REFERENCES


C. Y. Huang, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

P. Song, High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.

(Received November 1, 1991; revised August 13, 1992; accepted September 23, 1992.)