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STRUCTURE AND PROPERTIES OF THE SUBSOLAR MAGNETOPAUSE FOR NORTHWARD IMF: ISEE OBSERVATIONS

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Abstract. Detailed magnetopause structure and properties for the magnetic field, electric field and plasma are examined for an ISEE 1 magnetopause crossing which occurred near the subsolar point when the interplanetary magnetic field (IMF) was strongly northward. Because the crossing is slow, the spatial variations in the plasma are clearly resolved. This example illustrates the nature of the steady state interface of two magnetized thermal plasma populations with parallel fields and can serve as a guide to theoretical modeling and simulations. We have found that the magnetopause is composed of three layers, a sheath transition layer, an outer boundary layer and an inner boundary layer. In the sheath transition layer, there is a gradual density decrease without a change in temperature. The transition layer occurs totally within the magnetosheath plasma. The outer boundary layer and the inner boundary layer are dominated by magnetosheath and magnetospheric particles, respectively. In each of the boundary layers, the plasma can be interpreted as simple mixtures of the magnetosheath and magnetospheric populations. No significant heating or cooling is seen across the magnetopause during this crossing. The plasma within each of these layers is quite uniform and their boundaries are sharp, suggesting that there is very little diffusion present. The sharp boundaries between the transition layer, the boundary layers and the magnetosphere are all thinner than an ion gyroradius. Transverse waves with right hand or linear polarization near the ion gyrofrequency are observed in the transition layer. These appear to be generated in the transition layer and to be a common feature of this layer when the IMF is northward.

Introduction

Any transfer of mass, momentum or energy from the solar wind to the Earth must cross the magnetopause. Thus understanding the physical processes occurring in this boundary is crucial to understanding the coupling of the solar wind with the magnetosphere. Moreover, the knowledge may prove to be of more general use in understanding the interface between plasmas of quite distinct properties. Early studies concentrated on modeling the steady state structure of this boundary [Ferraro,1952; Parker,1967; Davies,1968; Su and Sonnerup, 1968; Sestero, 1964; Lee and Kan, 1979; see also reviews Willis, 1971; Sonnerup, 1976; Siscoe 1987]. After Dungey [1961] proposed that the terrestrial magnetic field would reconnect with southward interplanetary magnetic fields, processes expected at a reconnecting magnetopause were examined [Petschek, 1964; Levy et al., 1964; Sonnerup, 1970; Lee and Kan, 1982; Swift and Lee, 1983; Lee and Fu, 1985; Song and Lysak, 1988]. The direction of the interplanetary magnetic field (IMF), which controls the rate of reconnection, is perhaps the most important factor affecting the features of the magnetopause.

When the term "magnetopause" first appeared in the literature, it referred to the interface between the magnetosphere and the solar wind [Hines, 1963]. In this broadest of definitions, the magnetosheath and bow shock are included in the magnetopause. Since then the studies of the bow shock have become independent, and the region we call the magnetopause has become the interface between the shocked solar wind, or the magnetosheath, and the magnetosphere. Because the current layer, where the magnetic field changes in direction and/or magnitude, can usually be identified easily from the magnetic field measurements, this current layer is often used to deduce magnetopause motion [e.g. Berchem and Russell, 1982] and is sometimes referred to as the magnetopause, rather than the magnetopause current layer. On the other hand sometimes the magnetopause is indentified as the place where magnetospheric energetic particles start to appear [e.g. Williams, 1979], where the plasma starts changing temperature [e.g. Tsurutani et al., 1989] or where bursts of plasma wave turbulence are present [Gurnett et al., 1979]. All these definitions are useful when one is trying to identify this interface in broad terms or to give a reference time or location for the interface. However, observationally, the above features may not be coincident. Furthermore, physically, the current layer of the magnetopause contains only part of the physical processes involved in solar wind-magnetosphere coupling, and the physical processes within the current layer can be completely different for different IMF orientations. Based on these physical considerations, we define the magnetopause, in our study, as the interface between the shocked solar wind and the magnetosphere and not just the current layer.

The magnetopause current layer, first reported by Cahill and Amazeen [1963], has been

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studied in detail using magnetic field measurements [e.g. Aubry et al.,1971; Neugebauer et al., 1974; Elphic, 1989] since they are easier to obtain with sufficient time resolution than particle measurements. The co-orbiting ISEE -1 and 2 spacecraft enabled measurements of the thickness and motion of the magnetopause current layer. Its typical thickness is 500 ~ 1000 km, or 5 ~ 20 ion gyroradii and its typical speed is 15 ~ 45 km/s [Berchem and Russell, 1982].

On the earthward side of the current layer, a plasma region is often observed with properties different from the magnetospheric plasma. It is usually called the magnetospheric boundary layer or the Low Latitude Boundary Layer (LLBL) [Eastman et al.,1976; Haerendel et al., 1978; Eastman, 1979; Paschmann, 1979; Sckopke et al., 1981]. It is detected only sporadically. The cases which showed that the LLBL disappeared [e.g. Paschmann, 1979] could be caused either by the fast motion of the thin layer combined with the poor time resolution of plasma instruments, or, as Paschmann [1979] suggested, by the absence of a boundary layer at times. Since reconnection and related phenomena can effect the the LLBL, a systematic study of the boundary layer under different IMF conditions is needed.

Magnetopause properties may also be different in different regions. In the subsolar region, the bulk velocity of the magnetosheath flow is near zero. Free energy near the magnetopause is available principally from only the field shear, the gradient of density and temperature, and anisotropy. In the flank region, the magnetosheath flow velocity is a significant fraction of its upstream solar wind value. This flow can be a large source of free energy there. It can be much larger than that carried by density and temperature gradients. The question is whether the flow energy can be converted into other forms of energy through efficient physical processes. Song et al. [1988] have shown that the Kelvin-Helmholtz (K-H) instability is not an efficient mechanism to excite long period surface waves on the magnetopause, but it is still possible that small scale perturbations can be produced by the flow and that the K-H instability grows at the inner edge of the LLBL [e.g. Sckopke et al., 1982; Bythrow et al., 1986]. Therefore, we will study the subsolar magnetopause and the flank magnetopause separately. We would not be surprised if we found different processes occurring at the flank magnetopause.

In this paper we choose the subsolar region as our starting point for understanding the structure and properties of the magnetopause. We further simplify our analysis by restricting our attention to times when the IMF is strongly northward because subsolar magnetopause should be relatively simple for northward IMF. In this case, the problem becomes a steady state interface between two magnetized thermal plasma populations. We seek to determine the structure of the interface and how it is stabilized. There has been little progress in this area since the work of Lee and Kan [1979].

The difficulties which limit the observational study of the internal structure of the magnetopause arise essentially from the low time resolution of particle measurements. On the ISEE 1 and 2 spacecraft, the 2-D Fast Plasma Experiment has a maximum temporal resolution of 3 seconds and the 3-D particle detector has a resolution of 12 seconds at the highest bit rate. A typical magnetopause current layer crossing in contrast often lasts less than half a minute. It is difficult to identify the fine structure from a few fluctuating data points within the boundary. To solve this problem we searched for slow magnetopause crossings which occur in the rare situations when the magnetopause moves slowly relative to the spacecraft. A slow crossing can last as long as a few minutes in the current layer during which the ISEE plasma measurements are able to provide many samples of the plasma. To interpret these data solely in terms of spatial gradients we must assume that temporal variations are small, but we feel comfortable since slow crossings imply a stable magnetopause. "A stable magnetopause", here, means that the nature of the magnetopause is not changing but the whole structure can be in motion. By looking through the ten years of ISEE data we have found several long enduring crossings near the subsolar region and most of them occurred when the IMF was northward. This is consistent with Song et al. [1988], who show that the magnetopause is less oscillatory and hence is more likely to move slowly across the spacecraft when the IMF is northward.

In this paper we examine such a subsolar magnetopause crossing when the IMF is strongly northward and discuss the structure and properties of the magnetopause in this situation. We will discuss in detail a long enduring crossing when the IMF is strongly southward in a later paper.

A Slow Magnetopause Crossing

Figure 1 shows ISEE 1 data from a slow magnetopause crossing while ISEE 1 was inbound. It occurred at 12:01 LT, 0.0 GSM latitude and 10.86 R_e. This is close to the average subsolar distance of the magnetopause [Fairfield, 1971]. Thus, it is an ideal example to pursue our goal. Plasma data are from the Fast Plasma Experiment [Bame et al., 1978] with a time resolution of 6 seconds. Electric field data are obtained with the spherical double probe experiment [Mozer et al.,1978] with a time resolution of 0.5 second. Magnetic field data are from the fluxgate magnetometer [Russell, 1978] and displayed in the boundary normal coordinates [Russell and Elphic, 1978]. In these coordinates, N is normal to the boundary, sunward, L is along the magnetospheric field, northward, and M is dawnward. The normal was obtained under the assumption of no normal component of the magnetic field by taking it to lie along the vector cross product of the magnetosheath and magnetospheric fields. Since this crossing occurred at the subsolar point, L, M and N are very close to Z, -Y and X in GSE coordinates. ISEE 2 on that day was 7854 km ahead of ISEE 1. Though we could not use inter- spacecraft timing to determine the exact thickness of the magnetopause on this crossing from the

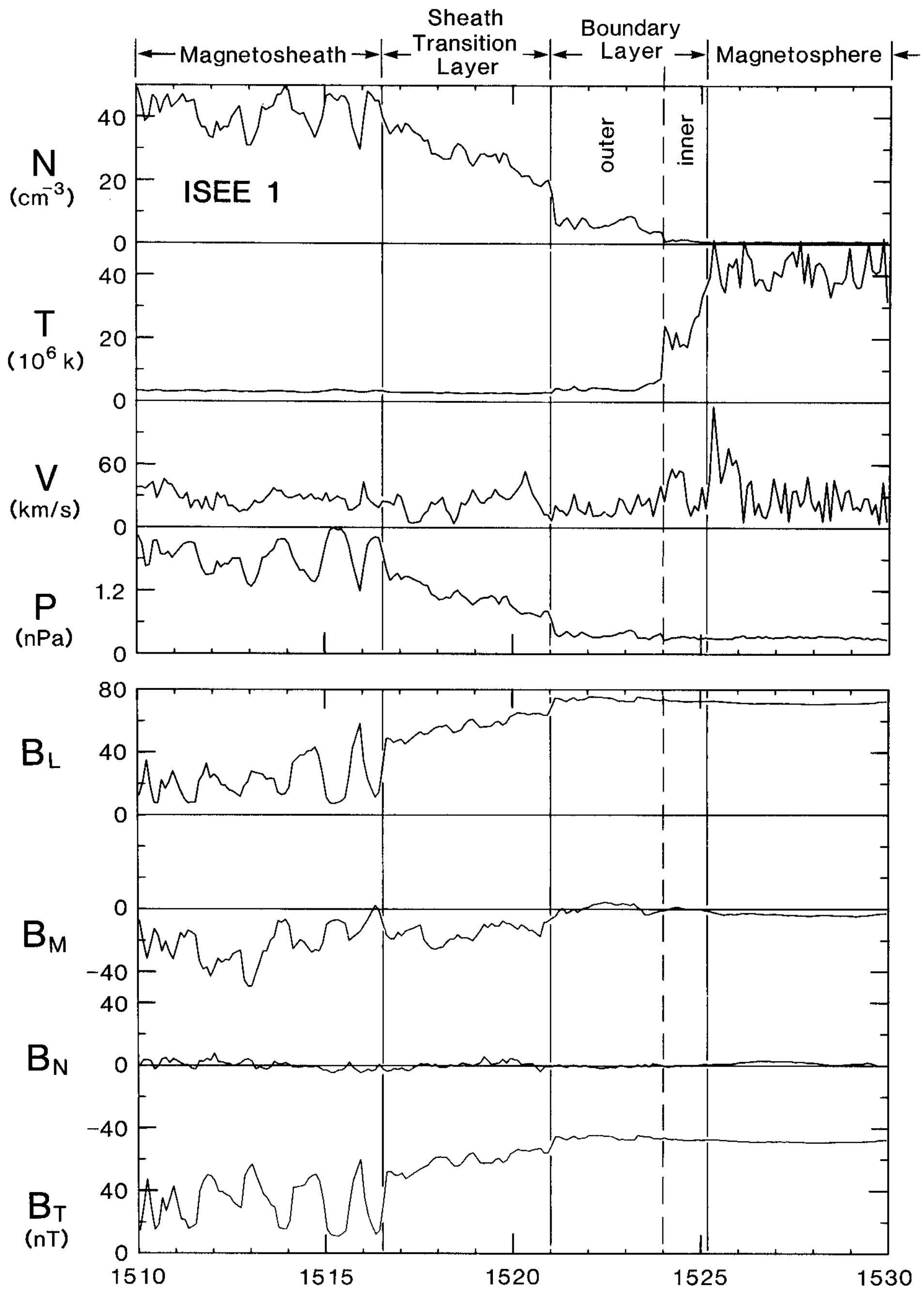

Fig. 1a. A slow magnetopause crossing by ISEE 1 on Nov. 1, 1978. The location of this crossing was at 12:01 LT, 0.0 MLAT and 10.86 R_e. (a) Plasma data with a time resolution of 6 seconds are from the FPE. N, T, V, and P are the ion density, cm^{-3}, temperature, 10^6 K, ion flow velocity, km/s, and ion pressure, nPa. The magnetic field data are from the fluxgate magnetometer and are presented in the boundary normal coordinates. The tangential discontinuity technique was used to determine the normal direction of the magnetopause. Regions are separated by vertical lines. The sheath transition layer is the region the magnetosheath plasma density changes. The outer boundary layer and the inner boundary layer are characterized by the sudden drop in the density and the sudden increase in the temperature.

magnetometer data, we can infer it from particle measurements and compare the inferred thickness with the average thickness of the magnetopause from earlier work. The flow velocity is very small and close to the limit of resolution of the instrument and it gives an upper limit of the normal component of 5 km/s relative to the spacecraft. The energetic particle data also

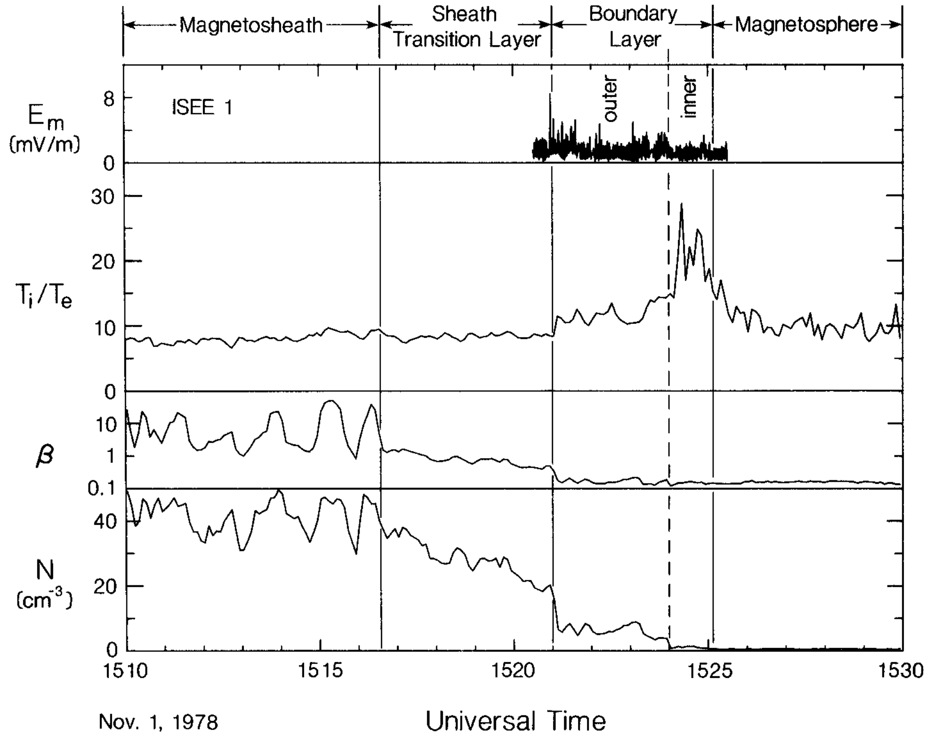

Fig. 1b. The electric field data, E_m, in mV/m, are from the quasistatic and low frequency electric field measurement with a time resolution of 0.5 second in s/c spin coordinates. T_i/T_e and β are the ratio of ion and electron temperature and the ratio of thermal and magnetic pressure.

provide an estimate of the thickness of the sharp boundary at 1524UT [T. A. Fritz, D. Mitchell and D. J. Williams, personal communication 1989]. Electrons with gyroradii less than 8 km are isotropic on the magnetosheath side and have large anisotropy on the magnetospheric side. Electrons with larger gyro radii keep some of the magnetospheric anisotropy on the magnetosheath side. Thus we estimate that the thickness of the sharp boundary at 1524UT is about 10 km. Since this boundary has timescale of 5 seconds based on the magnetic field data we obtain a velocity of 2 km/s. This is substantially slower than the typical magnetopause speed of 15 ~ 45 km/s. Using the velocity of 2 to 5 km/s, the thickness of the sheath transition layer, the same region as the magnetopause of Berchem and Russell [1982], is about 500 to 1300 km. This is consistent with Berchem and Russell [1982]. We note that a similar appearing magnetopause crossing was observed on Nov. 5, 1977 [Russell and Elphic, 1978; Paschmann et al., 1978; Parks et al., 1978] when the IMF was northward and ISEE 1 and 2 were closer together.

Since the direction of the IMF may be different from that of the magnetosheath field due to draping of the fields and transient variations in the solar wind may cause the magnetopause to oscillate [Song et al., 1988], we have to check the upstream conditions to ensure that there is no conflict with the above statements. Figure 2 shows 5-minute averages of the solar wind and IMF data for this crossing from ISEE 3. ISEE 3 was 196 R_e upstream. The time delay for solar wind flowing from ISEE 3 to ISEE 1 is about 51 minutes, obtained by dividing the separation along the Earth-Sun line by the solar wind velocity. The solar wind was quiet and with a value about the average dynamic

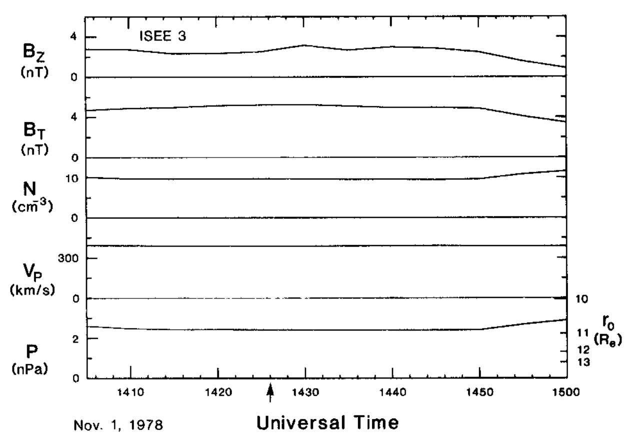

Fig. 2. The solar wind and interplanetary magnetic field data from ISEE 3 on Nov. 1, 1978. The location of ISEE 3 was (196,-79,8) R_e GSE. The time delay for the solar wind flowing from ISEE 3 to ISEE 1 was about 51 minutes. The time corresponding to the crossing is indicated by the arrow. B_z, B_t are the north component and the magnitude of the interplanetary magnetic field, in nT. N, V_p and P are the solar wind density, in cm^{-3}, velocity, in km/s, and dynamic pressure, in nPa. The predicted distance of the subsolar magnetopause is given on the right hand side of the bottom panel.

pressure based on 3 years of IMP-8 data. The IMF was strongly northward during that time. Thus, we expect the magnetopause to be quasi-stationary at this time. No IMP-8 data were available during this crossing.

Structure of the Magnetopause

The plasma and magnetic field measurements in Figure 1 can be divided into five distinct regions. Initially the spacecraft was in the magnetosheath where the ions are dense and relatively cool and the magnetic pressure and plasma pressure oscillate out of phase. Then the spacecraft enters a transition layer where the magnetosheath plasma decreases in density and the magnetic field strength increases to keep the total pressure constant. Next there are two boundary layers in which the density drops in two steps and the temperature rises. Finally the spacecraft enters the magnetosphere. The low frequency oscillations in the magnetosheath are mirror mode waves [Tsurutani et al., 1982]. The total pressure fluctuations caused by these oscillations are very small. Therefore, these oscillations will not cause significant magnetopause oscillations. They are a common feature of the magnetosheath but are beyond the scope of this paper. In this section we will examine each of the three internal regions of the magnetopause in turn starting with the sheath transition layer.

The Sheath Transition Layer. This region is the layer in which the sheath plasma decreases in density and the magnetic field increases so that the total pressure is constant. This layer carries the current associated with the increase in field strength upon entering the magnetosphere. In previous studies this was called the current layer. However, we refer to it here as the sheath transition layer to emphasize the importance of the variation of the plasma in this region. Figure 3 shows the magnetic field change in the form of a hodogram. Essentially the field increases its magnitude from the magnetosheath to the magnetosphere with little change in its direction. The duration of the crossing of this region was about 260 seconds. This long duration allowed 41 spectra to be measured with the fast plasma analyzer. As discussed in section 2, the thickness of this region is about 500 to 1300 km. T_i/T_e remains at the magnetosheath value, which is about 8. At the inner edge of the transition layer the magnetic field has nearly reached the magnetospheric value, but the particles still consist entirely of magnetosheath particles. In other words, the transition from an IMF configuration to a near geomagnetic field configuration occurs totally within the magnetosheath plasma.

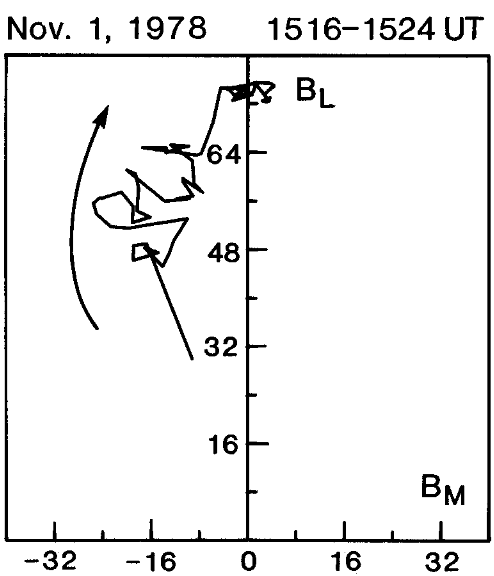

Fig. 3. The magnetic field hodogram in the sheath transition layer and the outer boundary layer crossing. B_n is not shown here since it is very small.

The Outer and the Inner Boundary Layers. The change from magnetosheath-like plasma to magnetospheric plasma during this crossing is composed of two layers. We will refer to them as the outer boundary layer (OBL) and the inner boundary layer (IBL). In the outer boundary layer, the ion density drops significantly from the transition layer level with little increase in the temperature. In the inner boundary layer, a further density drop accompanies a large increase in the temperature. T_i/T_e increases throughout the outer boundary layer and increases dramatically in the inner boundary layer due to a faster ion temperature increase than electron temperature increase. What is surprising is that there are at most weak gradients within each layer while they are separated by sharp boundaries. This form of density profile was also seen at the Nov. 5, 1977 magnetopause crossing [Paschmann, 1978]. The existence of these sharp gradients argues against the importance of diffusion in forming the boundary layers. The thickness of the outer boundary layer is about 380 km to 1000 km and the inner boundary layer's thickness is about 170 to 430 km for this crossing. It is hard to compare these two layers with the low latitude boundary layer observed in the flank region as mentioned in our introduction, but there are some similarities. For example, the inner boundary layer is very much like the halo region in the paper of Sckopke et al. [1981] and the outer boundary layer is similar to their low latitude boundary layer.

Plasma Properties

We can determine the history of the particles in each region by examining their distribution functions. Figure 4a shows the ion distribution function averaged over azimuth for the regions in and near the magnetopause. It has features similar to those found by Eastman et al. [1976] and in other boundary layer studies. There is a systematic decrease in the low energy population from the outermost to the innermost spectrum and a systematic increase in the high energy population. All distribution functions cross at almost the same point. To understand the implications of this feature, let us imagine a vertical line, say at 1 keV, on Figure 4a. If one curve, say the outer boundary layer spectrum, is above the magnetosheath and the sheath transition layer curves at energies greater than 1 keV, the outer boundary layer must have more particles above 1 keV than in the magnetosheath. The magnetosheath can not supply so many particles in this energy range. These particles must come either from the lower energy range of the magnetosheath particles through a heating process or from the magnetosphere. If the spectrum of the outer boundary layer exceeds that in the magnetosphere then the only possible source is a heating process. A cooling process would be indicated by a boundary layer spectrum falling below the magnetospheric and magnetosheath spectra. The boundary layer curves lie between those of the magnetosheath and magnetosphere. Therefore, we conclude that no significant heating or cooling process across the magnetopause is required when the IMF is northward. If we assume that the particles in the boundary layers are a simple mixture of the two populations, we can calculate the ratio of the two populations for each layer by using the observed moments of the distribution function, using the equations

$$N = N_c + N_h \quad (1)$$

$$P = T_c N_c + T_h N_h \quad (2)$$

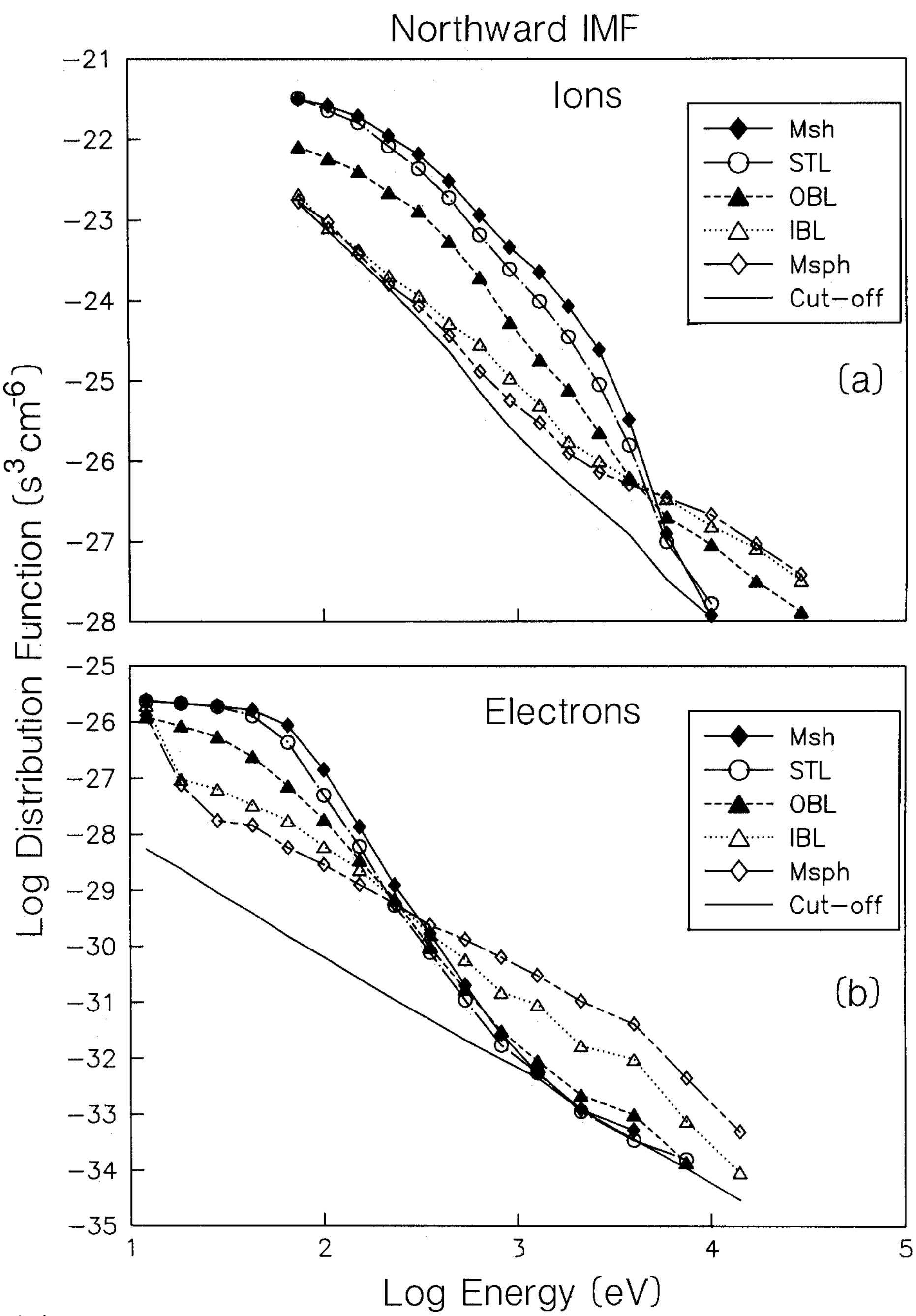

Fig. 4(a) Ion distribution function showing slices through the distribution functions for the regions in and near the magnetopause from the FPE. The distribution functions are averaged in the equatorial plane. (b) Electron distribution functions.

TABLE 1. Magnetic Field and Plasma Properties in the Magnetopause

Region	B nT	N_i cm^{-3}	T_i 10^6K	$N_c:N_h$	N_h/N_{sph}	N_c/N_{sh}	N_c/N_{ie}
Msheath	32	42	3.2				
Sheath TL	32-74	42-20	2.9			75%	
Outer BL	74	6.4	4.3	42:1	26%	15%	31%
Inner BL	73	1.1	23	1:1	93%	1.3%	3%
Msphere	71	0.6	42				

Subscripts:
i: ion, c: cool, h: hot, sh: sheath, sph: sphere, ie: inner edge of the sheath transition layer

where N, N_c, N_h, T_c, T_h and P are the total ion density, cool and hot populations, cool and hot ion temperature, and thermal pressure. We take the cool temperature to be that of the magnetosheath ions and the hot temperature to be that of the magnetospheric ions. The results are shown in Table 1. The ratio between cool and hot populations is 40:1 in the outer boundary layer and 1:1 in the inner one. We can also obtain similar results by using the distribution functions in Figure 4a. Thus, the magnetosheath population is dominant by number and energy density in the outer boundary layer, but the magnetospheric population is important in the inner boundary layer since magnetospheric particles carry more energy than magnetosheath particles carry. Figure 4b shows the electron distribution functions. With some differences they resemble those in Figure 4a. The differences are that the magnetosheath spectrum does not cross the transition layer spectrum and that the spectra of the inner boundary layer and the magnetosphere show enhancements at lowest energies. The former difference implies that there are very few hot electrons which leak from the magnetosphere into the sheath transition layer or the hot electrons disperse quickly. The latter difference is a more complicated issue. The measured flux of low energy electrons seems too high to be due to background electrons, so it is likely to be due to photoelectrons. When they are created they have a very low energy, less than 20 eV. There are two possible sources of photoelectrons. One is the spacecraft and the other is the ionosphere. The spacecraft potential dropped about 5 V at the boundary between the outer and inner boundary layers. Thus the measured distribution functions of the electrons in the inner boundary layer and magnetosphere have been artificially shifted by 5 eV due to the change in potential of the spacecraft. However, this change in the potential does not affect the spacecraft photoelectrons since they have crossed this potential twice but in opposite directions and therefore the spacecraft photoelectrons have no net gain in energy. The spacecraft photoelectron flux is expected to be ten times smaller than the observed photoelectron flux. Thus these photoelectrons may possibly come from the ionosphere by travelling along the field lines. If this is the case, then the inner boundary layer field connects to the geomagnetic field. However, according to this data set, it is not clear where the outer boundary layer field connects since the photoelectrons seen in the inner boundary layer and magnetosphere have an intensity similar to that of the outer boundary layer in the low energy range.

Magnetic Fluctuations

Figure 5 shows the power spectra of magnetic field strength for the three regions in the magnetopause from high time resolution, 1/4 second per sample, magnetometer data. The local maxima in the sheath transition layer and outer boundary layer are near the ion gyrofrequency. The waves in the sheath transition layer will be discussed later. The waves in the outer boundary layer are not common in other slow subsolar magnetopause crossings. The power in the transition layer is greater than that in the boundary layers at all frequencies. This can be the result of a larger free energy due to gradients in the sheath transition layer. The slopes for the transition layer and the inner boundary layer are similar, about -2. However, the outer boundary layer's spectrum is substantially steeper. Its slope is about -3.8.

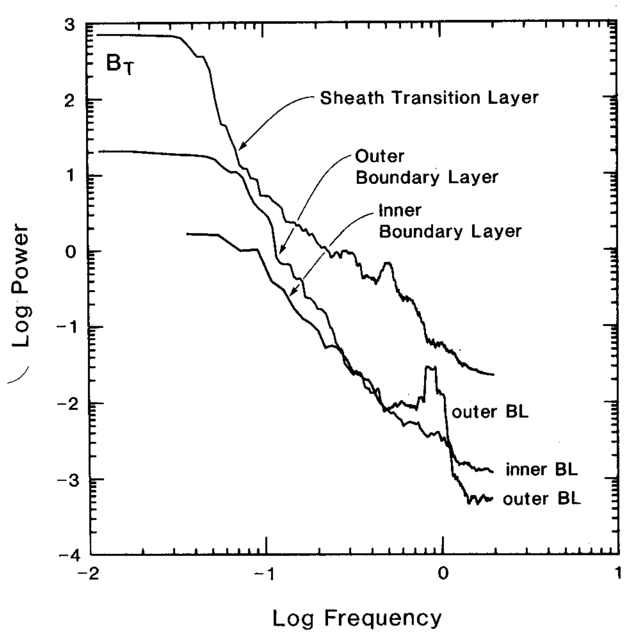

Fig. 5. Magnetic field power spectra for the three regions in the magnetopause.

The difference in slopes for each layer indicates that the physical processes are different in different layers or that the layers are at different stages of the nonlinear evolution of waves. Moreover, the fact that the outer boundary layer's slope is different from its neighbors implies that the three layers are isolated each other.

The high frequency waves in the sheath transition layer are shown in Figure 6. Figure 7 shows the power spectra of the three components. The center frequency of these waves is 0.55 Hz, ~ 0.5 f_{ci}, where f_{ci} is the ion gyrofrequency. The compressional power ratio, the ratio of the wave power parallel to the dc magnetic field relative to the total fluctuation power, is about 10%. The ellipticity of the waves is about 0.1 ~ 0.2. The direction of the maximum perturbation is along M, the dawn-dusk, direction and the direction of minimum perturbation is along L, north- south. Figure 8 shows the high- pass filtered magnetic field data. The bottom panel shows the magnetic field strength for reference. The low cut- off frequency was chosen as 0.4 Hz. The Nyquist frequency for our data is 2 Hz. It is obvious that the waves are enhanced in the transition layer and do not simply propagate into this layer from the magnetosheath.

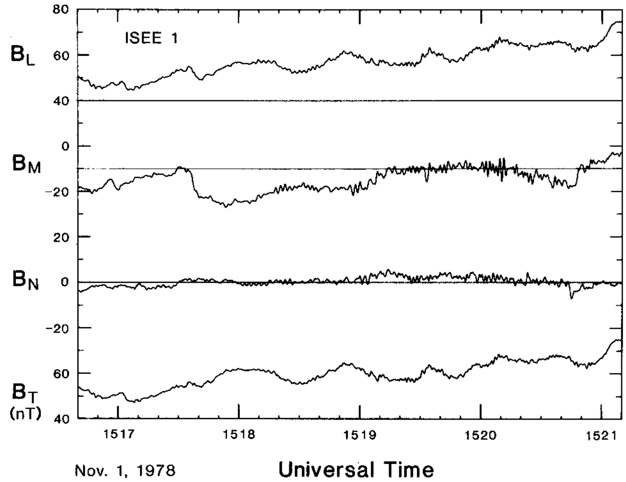

Fig. 6. High time resolution magnetic field data, 1/4 second per sample, in the sheath transition layer.

The waves observed here in the transition layer are not ion cyclotron waves since they are not left-handed waves. Thus, these waves should not interact strongly with the ions unless there are non-thermal ions traveling faster than the

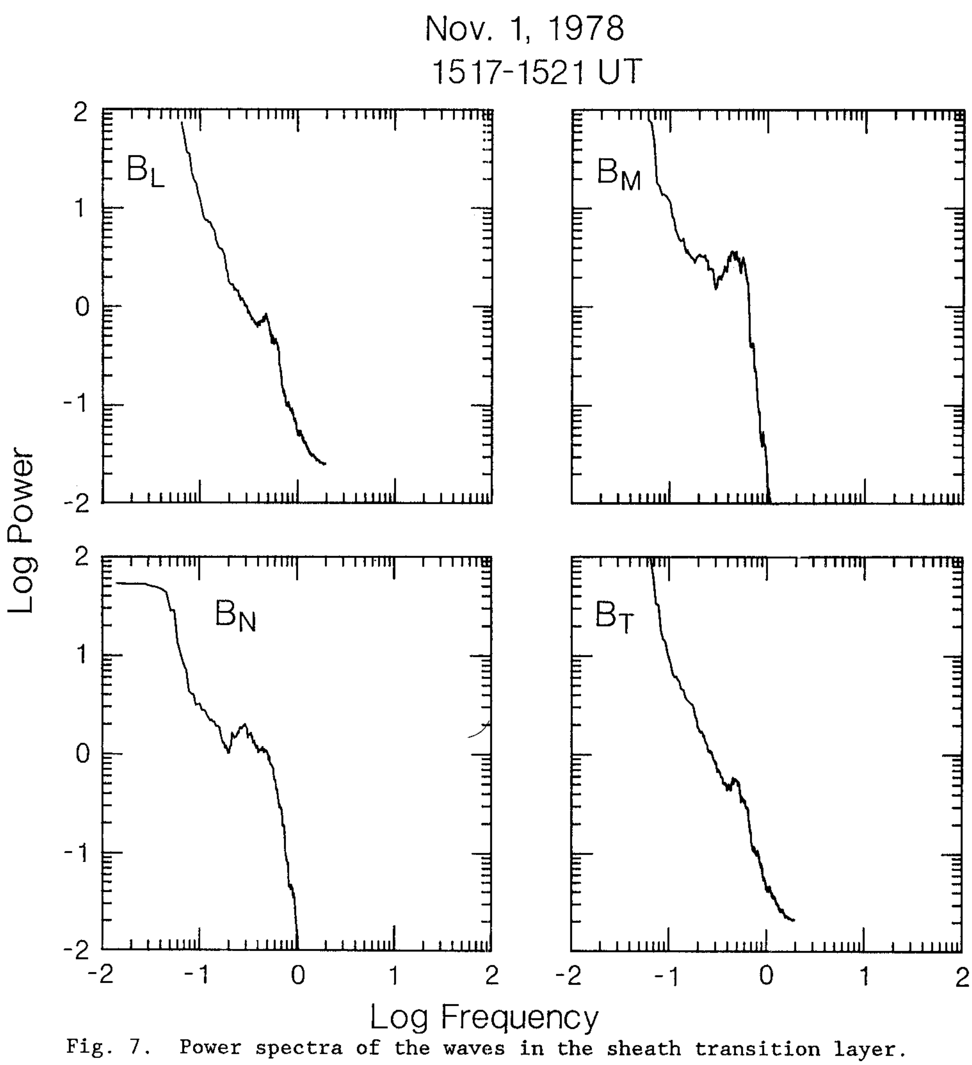

Fig. 7. Power spectra of the waves in the sheath transition layer.

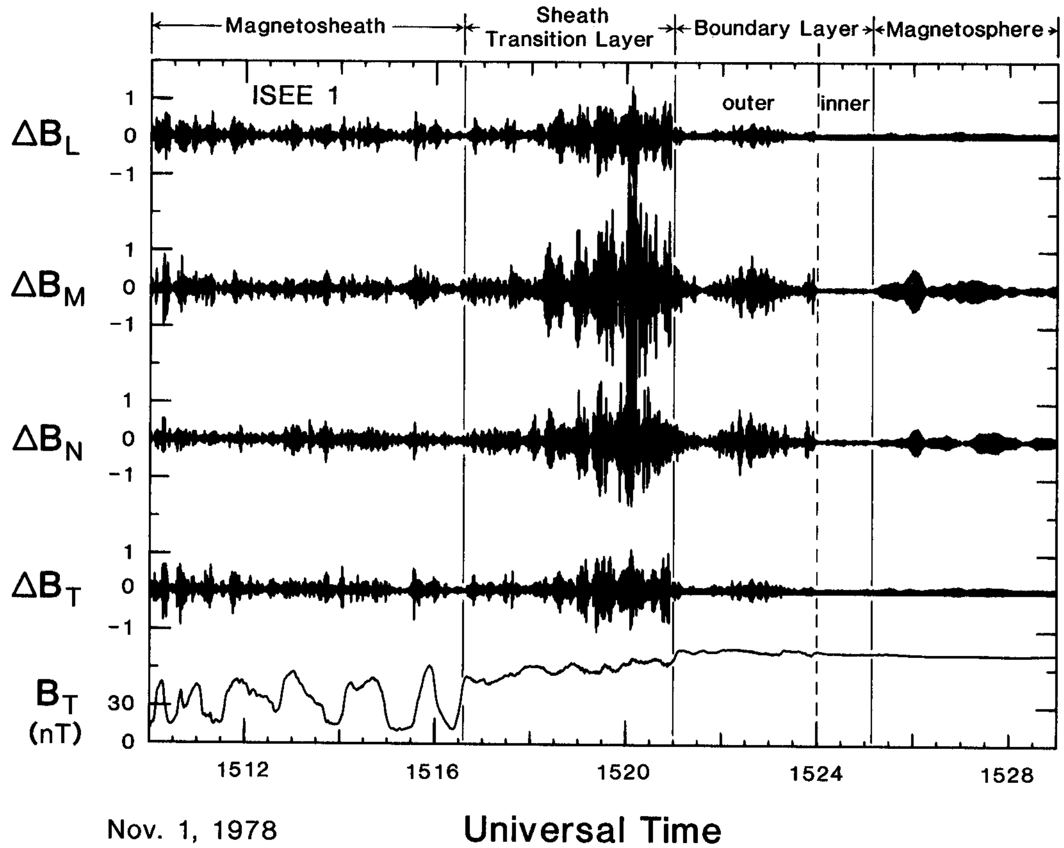

Fig. 8. High pass filtered magnetic field data on Nov. 1, 1978. The low cut off frequency is 0.4 Hz and the Nyquist frequency is 2 Hz. The maximum variation direction is M, dawn-dusk, direction. Waves are enhanced in the sheath transition layer.

waves and over taking them. This observation is consistent with the observed absence of heating or cooling across the magnetopause from particle measurements. Since the wave vector must be perpendicular to the field variation, its dawn-dusk component, which is the observed maximum variation direction, must be much smaller than the component in the noon meridian plane. So, these waves are not classical drift waves which propagate along the direction of the drift velocity [Mikhailovsky, 1968; Hasegawa, 1975] which is the dawn-dusk direction in this situation. However they may be gradient-driven waves since they appear to arise in the region with gradients. To estimate the wave length we multiply the Alfven velocity by the period of the wave. At the center of the wave activity (15:20UT), B ~ 64nT, n_i ~ 25.7cm^{-3}, V_A ~ 275 km/s and f ~ 0.55 Hz, we obtain λ ~ 500 km. This is of the order of the thickness of the sheath transition layer. Therefore, these waves provide a the clue to understanding what maintains the thickness of the transition layer.

The Boundaries Between the Layers

A striking feature of the magnetopause is that the three layers are separated by sharp boundaries. These boundaries form a stair-like structure in plasma parameters. They are about 10 km thick. From the measured plasma parameters we can calculate the expected possible scale lengths for this crossing: electron skin depth, c/ω_{pe}, ~ 1 km, electron gyroradius, r_{ce}, ~ 0.4 km, hybrid gyroradius, $\sqrt{r_{ci}\, r_{ce}}$, ~ 5 km, and ion gyroradius, r_{ci}, ~ 50 km. The former three are small enough to explain the thickness of the observed boundaries. The ion gyroradius is somewhat too large. In the absence of any neutralizing particles a charge imbalance caused by the excessive gyroradius of ions compared to electrons will cause a polarization electric field. This electric field will pull the ions backward and push the electrons outward. The final thickness of this boundary is $\sqrt{r_{ci}\, r_{ce}}$. This mechanism was discussed earlier by Ferraro [1952] and Dungey [1958]. It was thought at that time to be the thickness of the total magnetopause current layer. The sharp boundary between the sheath transition layer and the outer boundary layer is associated with a field change. We interpret this sharp boundary as the Ferraro-Rosenbluth current [e.g. pp. 307 of Akasofu and Chapman, 1972], or the Ferraro current for short. However, the situation is somewhat different from their picture. Here, the particles are in a magnetized thermal plasma with little flow speed, instead of a cold unmagnetized beam. The existence of the magnetosheath field makes the theoretical solution of this problem more complicated. We expect that the thickness of this boundary varies with the magnetosheath field orientation. There is very little change in the field at the boundary between the outer and inner boundary layers, which indicates little current flows on it.

If the thickness of the boundary is close to the hybrid gyroradius, there must be an electric field within this boundary. As shown in Figure 1b, the noise level of the electric field measurements during that time is about 3 mV/m. A peak which is about 8.5 mV/m appears at the boundary between the transition layer and outer boundary layer at 1521UT. To check whether this peak is the expected signature or not, we use a simple model to calculate the value of the expected electric field. We assume, as illustrated in Figure 9, that the electric field is uniform within the boundary and zero outside of the boundary and its direction is along x and that the magnetic field is uniform everywhere with its direction along z. Ions come into the boundary with a velocity v_0 perpendicular to the magnetic field and with an angle of incidence θ to x axis. The electric field will retard the particles and reflect them at the other end of the boundary, x = -L. The momentum equation and the boundary condition for these particles are:

$$\begin{cases} m\ddot{x} = q(\dot{y}B + E) & (3) \\ m\ddot{y} = -q\dot{x}B & (4) \\ x(0) = 0,\ \dot{x}(0) = -v_0\cos\theta, & \\ \ddot{x}(0) = (qE - q\,v_0 B\sin\theta)/m & (5) \\ \dot{x}(x=-L) = 0 & (6) \end{cases}$$

where m and q are the mass and the electric charge of a proton. Solving these equations for E, we obtain:

$$E = m/(2qL)\ (v_0^2\cos^2\theta - \omega_{ci}^2\ L^2) + v_0 B\sin\theta \quad (7)$$

Assuming the incident particles are uniformly distributed in θ, we can average over θ. Then

$$E = m/(4qL)\ (v_0^2 - 2\omega_{ci}^2\ L^2) \quad (8)$$

Using the parameters in the boundary between the sheath transition layer and the outer boundary layer, B ~ 65 nT, T_i ~ 2.9×10^6 K or v_0 ~ 155 km/s, and L ~ 10 km, we obtain E ~ 6 mV/m. A positive E_x is expected to be seen in the electric field data. The magnitude of the electric field was measured with the spin of the spacecraft as shown in Figure 10. If the electric field is as expected along x direction the peak measured at the boundary corresponds to 9.6 mV/m correcting for the direction of the antenna at that moment. This larger electric field is not inconsistent with our estimates because the electric field may not be uniform across the interface. The situation at the boundary between the two boundary layers is more complicated. Particles are on both sides of the boundary and they are different in nature. The assumption that particles are only on one side is not correct in this situation. The electric field observed between the outer and inner boundary layers has a smaller amplitude and over a larger region than we would predicted with our simple model.

Since there are large gradients of density and temperature at the boundaries, drift instabilities [e. g. Mikhailovsky 1983] might be expected to be excited. These instabilities could play an important role in helping particles to cross the boundaries. Table 1 shows the percentage content of particles in

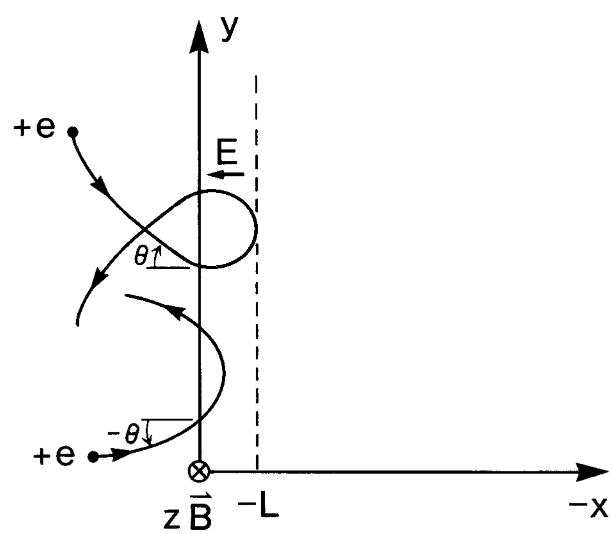

Fig. 9. Coordinates used to calculate the electric field in the boundary between the sheath transition layer and outer boundary layer. The electric field is along x direction. The magnetic field is along z direction. The electric field is constant within the boundary and zero outside. The magnetic field is constant everywhere. Particles enter a velocity V_0 and an angle of incidence θ to x axis in the xy plane. The thickness of the boundary is L.

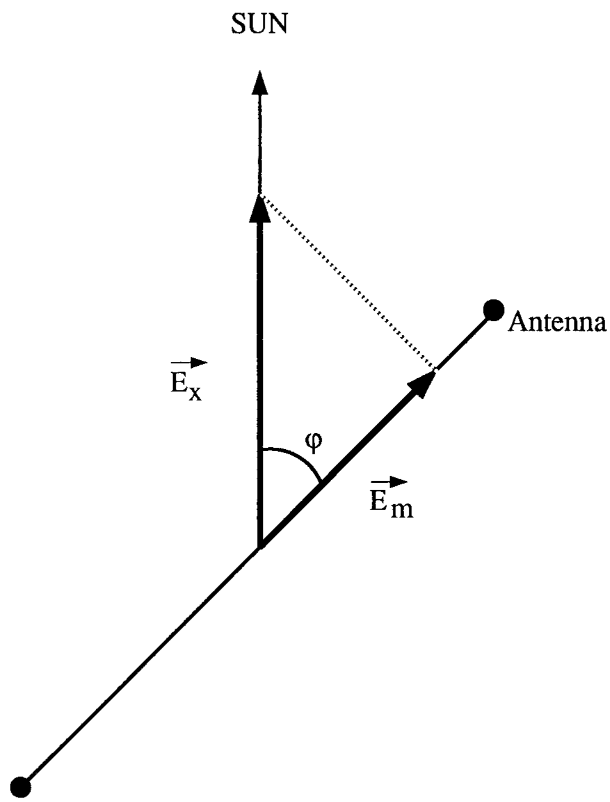

Fig. 10. Electric field antenna geometry. The electric field E_m was measured in s/c spin coordinates which is along the direction of the antenna. For a purely sunward field E_x = $E_m/\cos\phi$.

each layer. The density of magnetosheath particles in the outer boundary layer is one-third of that in the inner edge of the current sheet. The density of the magnetosheath particles in the inner boundary layer is only 10 percent of that in the outer boundary layer. There is very little density drop across the first boundary for the magnetospheric particles, but the density of the magnetospheric particles in the outer boundary layer is only a quarter as much as that in the magnetosphere.

While in theory the density of magnetospheric and magnetosheath particles found in the boundary layers can be supplied by diffusion, the existence of sharp boundaries and homogeneous boundary layers argue against diffusion as the mechanism controlling the boundary layers. Since the sharp boundaries are thinner than an ion gyroradius, diffusion cannot be occurring in these boundaries. If diffusion is the controlling mechanism within the boundary layers, we are presented with a paradox because the small gradient in density and temperature within each layer requires an unreasonably high diffusion rate in contrast to the low diffusion rate at the boundaries.

Summary and Discussion

The magnetopause crossing on Nov. 5, 1978 is composed of three layers. In the sheath transition layer, the magnetic field changes from the magnetosheath field to the magnetospheric field and the density decreases gradually, but the plasma is still magnetosheath plasma. The outer boundary layer and the inner boundary layer, which have similarities with the low latitude boundary layer and the halo near the flank magnetopause, are regions dominated by magnetosheath and magnetospheric plasma respectively. The plasma in these two boundary layers is quite homogeneous. The plasma in each layer consists of simple mixtures of the magnetosheath and the magnetospheric populations. No significant heating or cooling has been seen across the magnetopause during this crossing. The homogeneity of the boundary layers and the sharp boundaries argue against diffusion as the mechanism controlling the boundary layers. To maintain the plateaus in the boundary layers the diffusion coefficient would have to be very large but the sharp boundaries at the edges of the plateaus are too thin for diffusion to be present. The particle mixtures could be caused by momentary connection between the magnetospheric and sheath plasmas at high latitudes. However, we do not exclude the possibility that diffusion becomes more and more important away from the subsolar region.

We do not think that the number of the boundary layers is important. For example, we see three boundary layers in the Nov. 5, 1977 crossing. However, we do think the models which try to explain the formation of the boundary layer should be able to explain the multi-layered structure of the boundary layer. An interesting question is where the field lines in each layer connect, either to the earth or solar wind. Our results have confirmed that the field lines in the sheath transition layer connect with the solar wind, and the field lines in the inner boundary layer connect with the ionosphere, or closed field lines. We have not found where the field lines in the outer boundary layer connect.

Sharp boundaries between the sheath transition layer, the boundary layers and the magnetosphere are thinner than an ion gyroradius. Their thickness may be of the order of a hybrid gyroradius. The existence of strong electric field perturbations in the boundary between the transition layer and the outer boundary layer supports this argument. Therefore, the charge separation caused by different penetration of electrons and ions cannot be neutralized completely through the ionosphere in the crossing on Nov. 5, 1978. The physics, however, is more complicated than the Ferraro layer.

The magnetic field power spectrum in the frequency range from 0.07 Hz to 2 Hz for the outer boundary layer, which has a slope of -3.8, is very different from that for the transition layer and the inner boundary layer. The slopes of the power spectra for the transition layer and the inner boundary layer are about -2. This indicates that the three layers contain different physical processes or are at different stages of the nonlinear evolution of waves and that they do not communicate each other very well.

Right-handed or linearly polarized transverse waves with frequencies near the ion gyrofrequency appeared in the transition layer. Inspection of other slow crossings has shown that these waves also are present in other slow magnetopause crossings when the IMF was northward. The source of these waves appears to be inside the transition layer. These waves are neither ion cyclotron waves nor classical ion cyclotron drift waves. The wave length is of the order of the sheath transition layer. These waves may be the clue to understanding what controls the thickness of the transition layer, which is a long standing thearetical question. We think that the waves propagate normally to the boundary and possibly with a small tangential component or they can be standing waves within the layer. These waves try to minimize the gradients in the layer and consume the free energy due to the gradients. Thus, the transition layer maintains a thickness marginally stable to the instability which generates these waves.

The plasma depletion seen in the transition layer, which is associated with a part of the magnetopause current, may be similar to the effect studied by Lees [1964] and Zwan and Wolf [1976]. It is possible that this layer consists of streamlines of differing age. The plasma closest to the obstacle, the sharp boundary between the sheath transition layer and outer boundary layer, is moving the slowest and has the greatest opportunity be squeezed out along field lines [Zwan and Wolf, 1976] and to pitch angle diffusion along the field and reduce its density. However, the ion gyrofrequency waves in this region may add kinetic effects. The other contribution to the magnetopause current is from the boundary between the transition layer and the outer boundary layer. It is the diamagnetic current caused by a density gradient. Its thickness is perhaps as thin as a hybrid gyroradius and possibly changes with the magnetosheath field orientation. This part is similar to the Ferraro current.

There are still many outstanding questions to be answered about the underlying physics. We are continuing to study this crossing with plasma wave and 3-D particle measurements and to examine in detail other crossings of a similar nature.

Conclusions

We have studied in detail a magnetopause crossing which occurred near the subsolar point when the IMF was strongly northward to investigate the structure and the properties of the magnetopause as well as the physics inside in this region. Based on this crossing and another similar crossing which was well documented, we found that the subsolar magnetopause has multi-layered structure when the IMF is strongly northward. Each layer has relative uniform plasma in it and is separated by sharp boundaries. Both the wave and particle data show that the layers are isolated from each other. There is little diffusion. The boundary between the sheath transition layer and outer boundary layer functions like the Ferraro current. The sheath transition layer which carries much of the current is quite physically different from the Ferraro current. There are waves near the ion gyrofrequency in the sheath transition layer. These waves also occur in other slow subsolar crossings. They may be the key to understanding what maintains the thickness of the sheath transition layer.

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