

# Plasma Wave Turbulence at the Magnetopause: Observations From ISEE 1 and 2

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In this paper we investigate plasma wave electric and magnetic fields in the vicinity of the magnetopause by using recent measurements from the ISEE 1 and 2 spacecraft. Strong electric and magnetic field turbulence is often observed at the magnetopause. The electric field spectrum of this turbulence typically extends over an extremely large frequency range, from less than a few hertz to above 100 kHz, and the magnetic field turbulence typically extends from a few hertz to about 1 kHz. The maximum intensities usually occur in the magnetopause current layer and plasma boundary layer. Somewhat similar turbulence spectra are also sometimes observed in association with flux transfer events and possible 'inclusions' of boundary layer plasma in the magnetosphere. In addition to the broad-band electric and magnetic field turbulence, narrow-band electrostatic emissions are occasionally observed near the electron plasma frequency in the vicinity of the magnetopause. Two possible plasma instabilities, the electrostatic ion-cyclotron instability and the lower-hybrid-drift instability, are considered the primary candidates for explaining the broad-band electric field turbulence. The narrow-band electrostatic emissions near the local electron plasma frequency are believed to be either plasma oscillations or electrostatic waves near the upper-hybrid-resonance frequency.

## 1. INTRODUCTION

Because of the many important questions which have been raised recently concerning the physical processes which occur at the earth's magnetopause boundary [Heikkila, 1975; Haerendel et al., 1978], the study of the magnetopause has entered a period of increased activity. During the past year, magnetopause studies have been particularly aided by the launch of the ISEE 1 and 2 spacecraft [Ogilvie et al., 1978], which for the first time can provide basic information on the spatial-temporal structure of the magnetopause. In this paper we present an initial investigation of the plasma wave electric and magnetic fields associated with the magnetopause using data obtained from ISEE 1 and 2.

The importance of plasma wave observations near the magnetopause originates from the possible role which wave-particle interactions may play in the diffusion and transport of plasma across the magnetopause [Axford, 1964; Bernstein et al., 1964; Eviatar and Wolf, 1968; Hasegawa and Mima, 1978] and from the possible effects of plasma turbulence on energy dissipation and reconnection at the magnetopause [Syrovatski, 1972; Huba et al., 1977; Haerendel, 1978]. Plasma and magnetic field measurements have now been obtained at the magnetopause under a wide variety of conditions [Sonnerup and Cahill, 1967; Hones et al., 1972; Akasofu et al., 1973; Crooker and Siscoe, 1975; Rosenbauer et al., 1975; Paschmann et al., 1976; Eastman et al., 1976; Haerendel et al., 1978]. For a recent review of the various plasma regimes associated with the magnetopause, see Eastman and Hones [1978]. These measurements show that the magnetopause is often very turbulent, with considerable evidence of large-amplitude low-frequency

waves. Although the magnetopause is known to be very turbulent in the low-frequency MHD portion of the spectrum, relatively little is known about the plasma wave intensities at higher frequencies in the region of primary importance for microscopic plasma processes. Neugebauer et al. [1974] and Fairfield [1976] have investigated magnetic measurements of whistler-mode and ion-cyclotron waves near the magnetopause. However, no plasma wave electric field measurements have yet been reported in association with the magnetopause.

As will be shown in this paper, strong electric and magnetic field turbulence is frequently observed at the magnetopause. The electric field spectrum of this turbulence typically extends over an extremely large frequency range, from less than a few hertz to above 100 kHz, and the magnetic field turbulence typically extends from a few hertz to about 1 kHz. This frequency range includes nearly all of the characteristic frequencies of the plasma, from the proton gyrofrequency to the electron plasma frequency. The maximum intensities of both the electric and the magnetic field turbulence are usually confined to a region which includes the plasma boundary layer and the magnetopause current layer. Somewhat similar turbulence spectra are also sometimes observed in association with flux transfer events of the type described by Russell and Elphic [1979] and possible 'inclusions' of boundary layer plasma into the magnetosphere as described by Paschmann et al. [1979].

To facilitate the comparison of the plasma wave measurements with the plasma and magnetic field measurements, some of the magnetopause crossings have been selected from the crossings previously analyzed by Paschmann et al. [1979] and Russell and Elphic [1979]. For a description of the plasma wave instrumentation used in this study, see Gurnett et al. [1978]. Descriptions of the plasma and magnetic field instrumentation are given by Bame et al. [1978] and Russell [1978], respectively.

## 2. SOME REPRESENTATIVE MAGNETOPAUSE CROSSINGS

To illustrate the intensity and primary characteristics of plasma waves observed at the magnetopause a series of magnetopause crossings have been selected for analysis from four

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passes through the magnetosphere in November and December 1977. These passes were selected primarily on the basis of the plasma wave activity observed at the magnetopause. In each case an easily identified burst of plasma wave turbulence is present at the magnetopause. Because of this selection criterion the magnetopause crossings shown probably cannot be regarded as typical, since they were selected on the basis of enhanced plasma wave intensities. Further studies will therefore be needed to fully characterize the entire range of plasma wave turbulence which can occur at the magnetopause and the factors which control the intensity of the turbulence. The present study is intended mainly to illustrate the relationships observed for cases in which some plasma wave turbulence is known to be present.

The crossings selected occur over a range of local times extending from local morning,  $\sim 0600$  hours, to near the subsolar point,  $\sim 1200$  hours. In all cases the latitude of the crossing is relatively low, less than  $27^\circ$ . For three of the sets of crossings, two on November 10 and one on December 2, the  $Z$  component of the magnetosheath magnetic field in solar ecliptic

coordinates is strongly southward, whereas for the remaining crossing, on November 3, the  $Z$  component of the magnetosheath field ranged from near zero to slightly southward. The inbound crossings on November 10 and December 2 also occurred unusually close to the earth, at  $\sim 7.4 R_E$  and  $\sim 6.7 R_E$ , whereas the crossings on the other two days are close to the nominal magnetosheath position.

#### Crossings of November 10, 1977

Figure 1 gives an overall view of the plasma wave electric and magnetic fields detected by ISEE 1 on this day. The field strengths in each channel are shown on a logarithmic scale with a dynamic range of 100 dB. For the electric field the field strengths vary from about  $0.1 \mu\text{V m}^{-1}$  to  $10.0 \text{ mV m}^{-1}$  from the baseline of one channel to the baseline of the next higher channel. For the magnetic field plots the background noise level is adjusted such that it is near the bottom of the scale. The background noise levels of the magnetic sensors are given by Gurnett *et al.* [1978]. The solid line indicates the maximum field strength computed over intervals of 144 s, and the solid

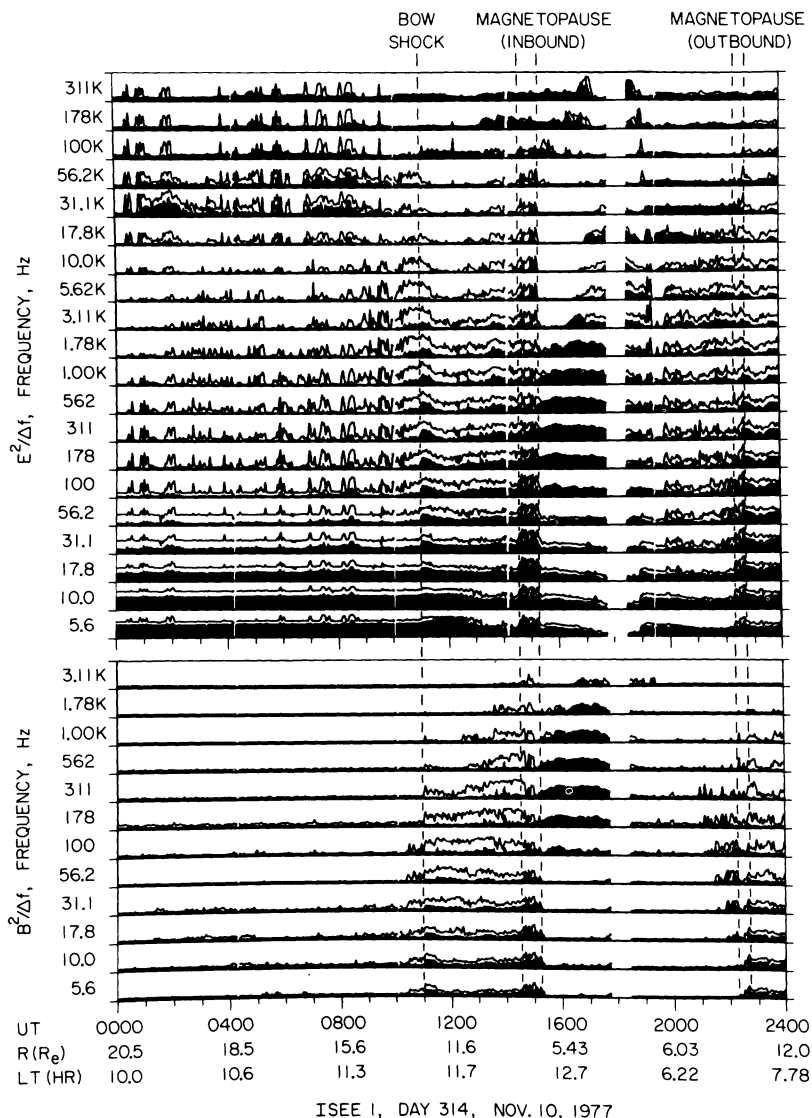


Fig. 1. The plasma wave electric and magnetic field data from ISEE 1 for a representative pass through the magnetosphere. The enhanced electric and magnetic field intensities at the inbound and outbound magnetopause crossings are clearly evident.

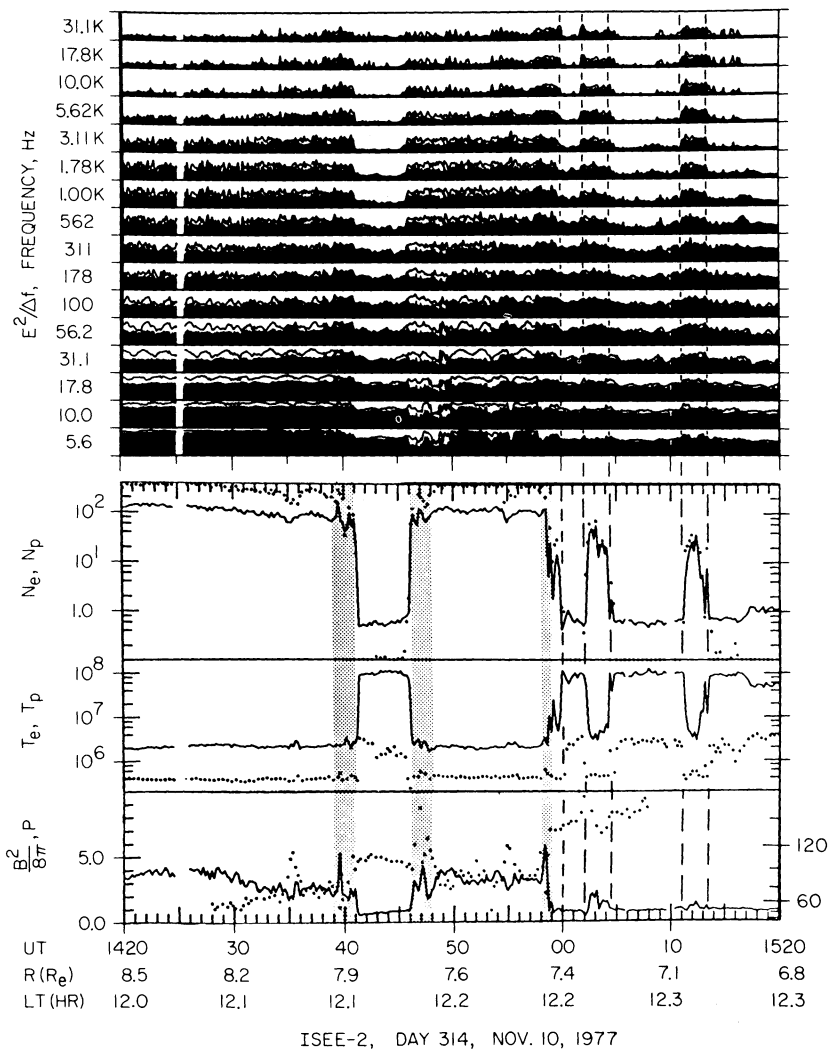


Fig. 2. A detailed comparison of the plasma wave electric field intensities detected by ISEE 2 with the corresponding plasma parameters obtained from the LASL/MPI fast plasma analyzer for the inbound series of magnetopause crossings in Figure 1. The electron and proton densities,  $N_e$  and  $N_p$ , in  $\text{cm}^{-3}$ , and electron and proton temperatures,  $T_e$  and  $T_p$ , in degrees kelvin, are indicated by dots and solid curves, respectively. The plasma pressure  $P$ , in units of  $10^{-8}$  dynes  $\text{cm}^{-2}$  on the left scale, is shown by the solid curve in the bottom panel, and the magnetic field pressure, given as magnetic field strength in gammas on the right scale, is shown by the dotted curve in the bottom panel. The dotted areas indicate the position of the magnetopause current layer crossing (see Figure 3).

black area indicates the average field strength computed over the same interval. On the inbound pass, the spacecraft approaches the earth from the dayside of the magnetosphere, passes through perigee at about 1800 UT in the local evening, and recedes away from the earth on the local morning side of the magnetosphere. The approximate positions of the bow shock, the inbound magnetopause crossings, and the outbound magnetopause crossings are indicated at the top of Figure 1. On the inbound portion of the pass, a series of magnetopause crossings and near encounters occurs from about 1440 to 1512 UT. These crossings and near encounters can be clearly identified in Figure 1 by the greatly enhanced electric and magnetic field intensities during this interval. This series of crossings occurs near the subsolar point at a magnetic latitude of about  $15.2^\circ$  and a local time of about 12.2 hours. On the outbound portion of the pass, another series of magnetopause crossings occurs from about 2220 to 2240 UT, with similar enhancements evident in the electric and magnetic field intensities. This series of crossings occurs at a magnetic latitude of about  $17.8^\circ$  and a local time of about 7.5 hours.

The ISEE 2 electric field intensity variations for the inbound series of magnetopause crossings are shown in greater detail in Figure 2 and compared with the plasma parameters obtained from the Los Alamos Scientific Laboratory/Max-Planck-Institut (LASL/MPI) fast plasma analyzer. A corresponding comparison of the ISEE 1 electric and magnetic field intensities and the magnetic field variations from the UCLA flux gate magnetometers on ISEE 1 and 2 is shown in Figure 3. The orthogonal  $NLM$  coordinate system used for the magnetic field measurements has the  $N$  axis perpendicular to the magnetopause and the  $L$  axis along the projection of the solar magnetospheric  $Z$  axis onto the magnetopause. The  $M$  axis completes the right-hand coordinate system. See *Russell and Elphic [1979]* for the method of determining the magnetopause normal. Unfortunately, during this portion of the pass the ISEE 1 plasma analyzer was turned off, so no direct wave-plasma comparisons could be made with the ISEE 1 data. However, as can be seen from the ISEE 1 and 2 magnetic field comparisons in Figure 3, the time delays between the two spacecraft are sufficiently small ( $<1$  min) that the

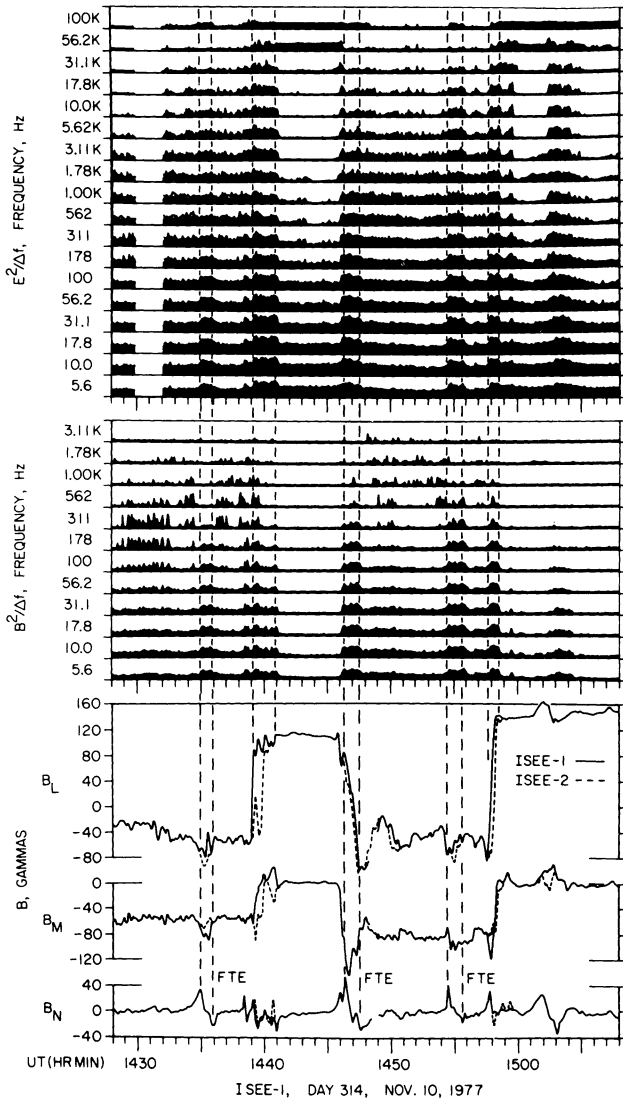


Fig. 3. A detailed comparison of the plasma wave electric and magnetic field intensities with the UCLA magnetic field measurements for the inbound series of magnetopause crossings in Figure 1. The times indicated by the dashed lines marked FTE correspond to the flux transfer events discussed by *Russell and Elphic* [1979]. Both the flux transfer events and the crossings of the magnetopause current layer are characterized by greatly enhanced electric and magnetic field intensities.

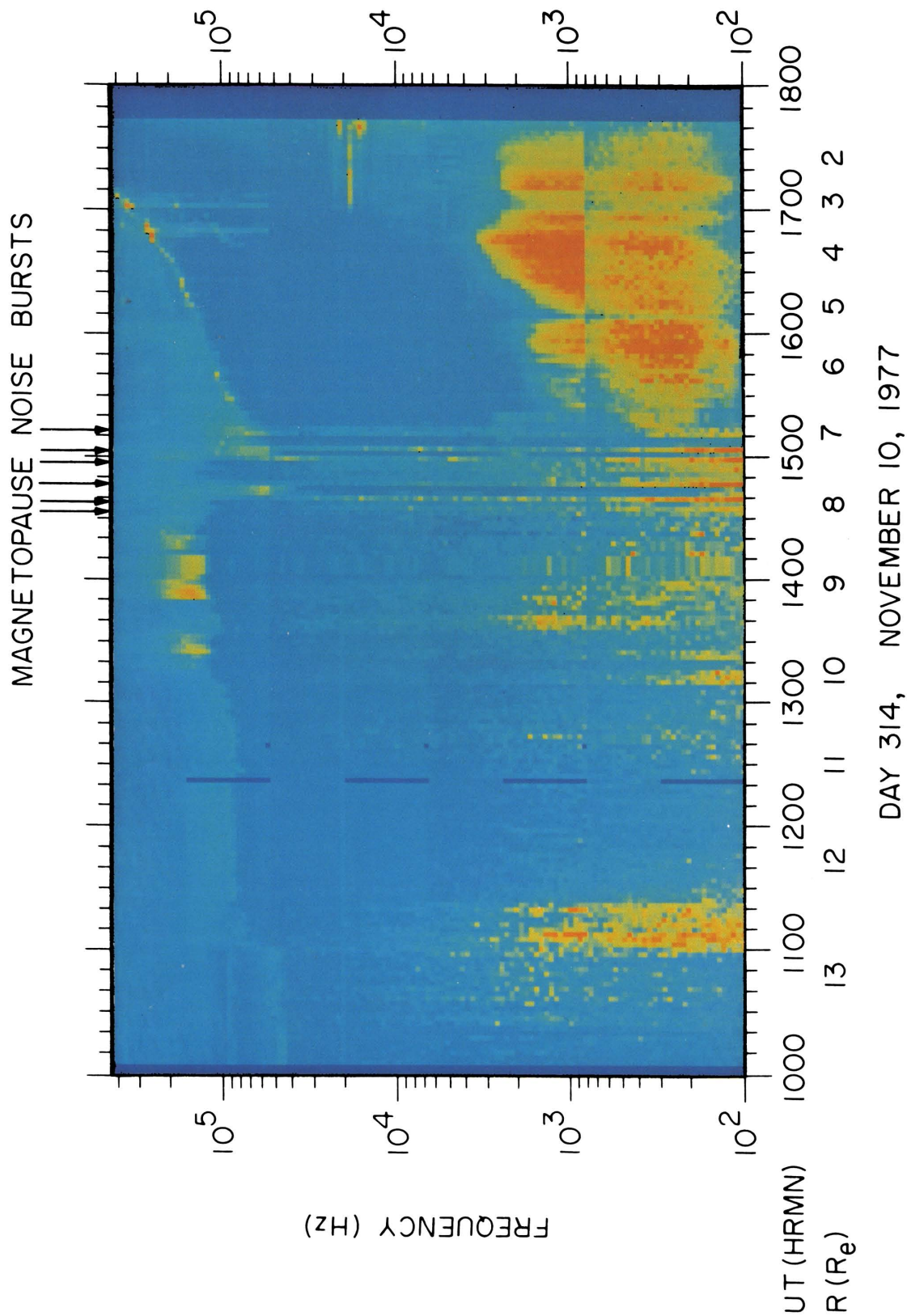
plasma parameter variations can be considered nearly identical on the time scales shown.

The plasma and magnetic field characteristics for the magnetopause crossings in Figures 2 and 3 have been previously analyzed and discussed by *Paschmann et al.* [1979] and *Russell and Elphic* [1979]. These results will be briefly reviewed for the purpose of comparison with the wave data. The vertical dotted areas in Figure 2 indicate the positions of the magnetopause current layer as deduced from the abrupt transitions in the magnetic field shown in Figure 3. The first crossing at 1440 UT appears to have a thin plasma boundary layer from about 1440 to 1441 UT. This interpretation is somewhat uncertain because small magnetic field variations are still present in this region, which could indicate that the spacecraft is still in the current layer. The second crossing at 1447 UT apparently has no boundary layer, since the onset of the magnetic field transition is essentially coincident with the abrupt in-

crease in the plasma density. The third crossing at 1458:30 UT has a very clearly defined boundary layer which extends from about 1459 to 1500 UT. The abrupt increases in the plasma density from about 1502 to 1504:30 UT and from about 1510 to 1513:30 UT have been interpreted by *Paschmann et al.* [1979] as either inclusions of magnetosheathlike plasma within the magnetosphere or a sudden switch-on of the boundary layer. Other events of interest during this crossing include the flux transfer events (FTE) identified by *Russell and Elphic* [1979] at 1435:30, 1447, and 1455 UT. These events are most easily identified by the characteristic variation of the  $B_N$  component of the magnetic field, usually consisting of a brief positive excursion followed by a somewhat asymmetric negative excursion.

Essentially all of the events described above have a clearly identifiable signature in the plasma wave electric and magnetic field data. The electric field spectrum variations are most easily seen for the ISEE 1 data in Figure 3, since the ISEE 2 data have relatively high levels at low frequencies apparently caused by interference from the spacecraft solar arrays. The flux transfer events at 1435:30, 1447, and 1455 UT, the magnetopause current layer and boundary layer crossings at 1440, 1447, and 1458:30 UT, and the plasma inclusions at 1503 and 1512 UT all have a very similar signature, consisting of a broad bandwidth burst of electrostatic noise extending from below 5.6 Hz up to about 100 kHz and a corresponding broad bandwidth burst of magnetic noise extending from below 5.6 Hz up to about 1 kHz. The broad bandwidth burst of electric field noise associated with each of these magnetopause crossings can also be easily identified in the high-resolution sweep frequency receiver data shown in Plate 1. The width of the noise burst at each magnetopause crossing corresponds very well to the combined width of the magnetopause current layer and the plasma boundary layer. The inner earthward boundary of the region of enhanced plasma wave turbulence is extremely sharp and coincides almost exactly with the abrupt drop in the plasma density from values characteristic of the magnetosheath/boundary layer plasma to values characteristic of the outer magnetosphere. The outer boundary of the region of enhanced plasma wave turbulence is not as sharp, suggesting that the turbulence extends outward into the magnetosheath to varying degrees, depending on the frequency. As can be seen from Figure 1, the magnetosheath always has a substantial level of electric field turbulence [see *Rodriguez, 1979*], which in some frequency ranges, from about 100 Hz to 3 kHz, for example, is nearly as intense as the noise at the magnetopause.

Detailed comparisons of the plasma wave, plasma, and magnetic field data for the outbound series of magnetopause crossings on November 10 are shown in Figures 4 and 5. These crossings show many of the same characteristics as the inbound pass near local noon except that the boundaries are not as sharp and the transition takes place over a larger spatial region. The magnetopause current layer crossing is located at about 2239 UT, as determined from the UCLA magnetic field data in Figure 5. On the magnetosphere side of the current layer, several regions of boundary layer plasma are evident in Figure 4 from about 2228 to 2232 UT, 2235 to 2237 UT, and 2237:30 to 2239 UT. A close approach to the boundary layer plasma also occurs from about 2222 to 2224 UT. Each of these regions is characterized by strongly enhanced electric and magnetic field intensities extending over a broad range of frequencies. Several intense narrow-band bursts of electric field



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Plate 1. The high-resolution sweep frequency receiver spectrogram for the inbound ISEE 1 pass illustrated in Figures 1 and 3. The intensities are color coded in blue through red with a dynamic range of 80 dB. The intense broad-band electric field turbulence associated with the magnetopause current layer crossings and flux transfer events can be clearly identified by the narrow vertical spikes extending across nearly the entire frequency range at the times indicated at the top of the spectrogram.

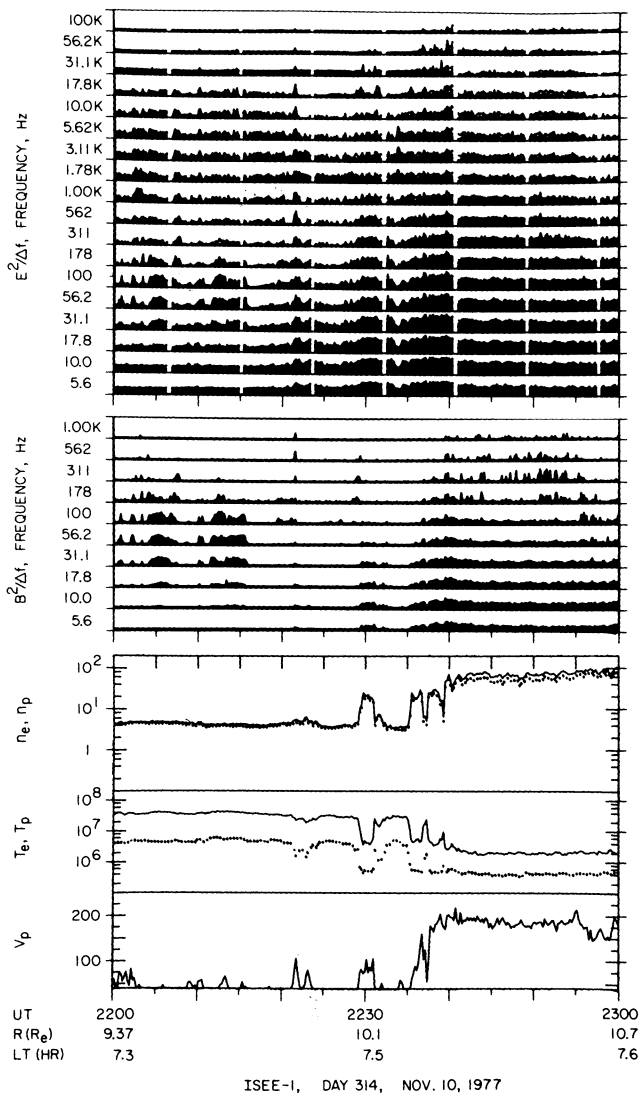


Fig. 4. A detailed comparison of the plasma wave electric and magnetic field intensities and the plasma parameters for the outbound magnetopause crossing in Figure 1. The proton flow velocity  $V_p$  is in units of kilometers per second. Several distinct encounters with the plasma boundary layer can be seen before the spacecraft crosses the magnetopause current layer at about 2239 UT (see Figure 5). Each of these encounters with the boundary layer is associated with enhanced plasma wave electric and magnetic field intensities.

noise are also evident in the 31.1- and 56.2-kHz frequency channels at about 2239–2240 UT, near the outer edge of the magnetopause current layer.

#### Crossings of December 2, 1977

Another series of magnetopause crossings, observed during the inbound pass on December 2, 1977, is shown in Figures 6 and 7. Three clearly defined magnetopause crossings, at about 0209, 0223, and 0328 UT, can be identified on this pass. The plasma wave data show a considerable amount of turbulence and wave activity throughout the entire interval shown in Figure 6, both inside and outside of the magnetosphere. Both the electric and the magnetic field data show enhanced broad-band wave intensities near the magnetopause crossings, from about 0200 to 0209 UT for the first crossing, from about 0223 to 0224 UT for the second crossing, and from about 0318 to 0328 UT for the third crossing. These regions of enhanced

wave intensity are particularly evident in the magnetic field channels from 5.6 to about 311 Hz. Corresponding enhancements in the electric field intensities, although they are not as distinct, can be seen for frequencies extending as high as 56.2–100 kHz. Comparisons with the plasma data show that these regions of enhanced wave intensities are all associated with large fluctuations in the flow velocity and a general increase in the plasma temperature above the nominal magnetosheath values, as would be expected in a boundary-layer-like region. Other periods of enhanced electric and magnetic field intensities, such as from 0302 to 0304 UT and from 0311 to 0315 UT, appear to correspond to close approaches to the boundary layer region.

Examination of the UCLA magnetic field data in Figure 7 for this pass shows a series of multiple crossings of the magnetopause current layer from about 0204 to 0209 UT, a single distinct crossing at 0223 UT, and a final series of multiple crossings from about 0322 to 0328 UT. Except for the final transitions the multiple current layer crossings from 0204 to 0210 UT and from 0322 to 0328 UT apparently are associated with brief excursions into the boundary layer and do not represent crossings into the magnetosphere, since at no time during these intervals does the plasma density drop to values characteristic of the outer magnetosphere. As can be seen from Figure 6, the final entry into the magnetosphere on these crossings occurs at about 0210 and 0328 UT. In contrast, the current layer crossing at 0223 UT is very sharp and distinct and apparently has only a very thin boundary layer. Comparisons with the UCLA magnetic field data show that the enhanced plasma wave intensities are closely associated with the regions of irregular magnetic field fluctuations.

#### Crossings of November 3, 1977

Another series of magnetopause crossings, observed during the inbound pass on November 3, 1977, is shown in Figures 8 and 9. As can be seen from the UCLA magnetic field data in Figure 9, five distinct crossings of the magnetopause current layer can be identified on this pass, at 0740:30, 0741:00, 0741:20, 0743:50, and 0751:30 UT. The plasma data in Figure 8 show that ISEE 1 entered the boundary layer between the first two pairs of current layer crossings but did not cross into the low-density high-temperature region of the outer magnetosphere. The last magnetopause current layer crossing at 0751:30 UT is followed by a broad region of boundary layer plasma with a density intermediate between the magnetosheath and magnetospheric densities. At several points within this plateau region, abrupt drops in the density, and associated temperature increases, occur which indicate close encounters with the earthward edge of the boundary layer. The final crossing from the boundary layer into the magnetosphere occurs at 0802:45 UT.

As can be seen from a detailed comparison of Figures 8 and 9, enhanced broad-band electric field intensities extending up to about 17.8 kHz are clearly observed when the spacecraft is in the boundary layer. However, in contrast to the previous cases analyzed, the magnetic field intensities in the boundary layer are quite low at all frequencies. Only a very small, 3-dB increase in the magnetic field intensities above the sensor noise level can be seen in the boundary layer.

#### 3. SPECTRUM, POLARIZATION, AND WAVELENGTH

To identify the plasma wave modes responsible for the electric and magnetic field turbulence observed at the magneto-

pause it is necessary to determine as much as possible about the spectrum, polarization, and wavelength of this turbulence. In the following we summarize the basic characteristics of the waves observed near the magnetopause, using specific examples to illustrate the typical characteristics.

### Spectrum

The most striking features of both the electric and the magnetic field turbulence observed at the magnetopause are the very broad bandwidth and the rapid decrease in the intensity with increasing frequency. For the electric field the turbulence spectrum usually extends from below a few hertz to about 100 kHz, and for the magnetic field the spectrum extends from below a few hertz to about 1 kHz, above which the intensity is usually below the instrument noise level. Typical spectra of the magnetosheath electric and magnetic fields are shown in Figure 10. These spectra were selected from the first magnetopause crossing in Figure 3 and cover a 1-min interval centered on 1440:00 UT. The peak spectral densities observed over this 1-min interval are shown by the solid curves, and the average spectral densities are shown by dashed curves. Except for the isolated peak in the electric field spectrum at about 31.1 kHz, both the electric and the magnetic field spectral densities are monotone decreasing functions of frequency. Both spectra fit a power law frequency dependence to a good approximation,

with  $E^2/\Delta f \propto 1/f^{2.2}$  for the electric field and  $B^2/\Delta f \propto 1/f^{3.3}$  for the magnetic field. The large difference, a factor of 10–100, between the peak and the average spectral densities indicates that the field strengths fluctuate rapidly, with many short intense bursts. The peak broad-band field strengths for the examples illustrated in Figure 10, integrated over the entire frequency range measured, are  $E \approx 5.2 \text{ mV m}^{-1}$  and  $B \approx 1.3$  gammas. These broad-band field strengths are reasonably typical of all the magnetopause crossings investigated in this study.

As can be seen from examination of some of the magnetopause crossings discussed in the previous section, it is sometimes difficult to distinguish the magnetopause boundary layer turbulence from the electrostatic noise commonly observed throughout the magnetosheath. This is in strong contrast to the interface between the boundary layer and the magnetosphere, which usually has a sharp drop in the electric field noise levels. Careful examination, however, reveals significant differences in the electric field spectrum between the magnetopause and the magnetosheath. Usually the electric field intensities at the magnetopause are significantly larger than the magnetosheath, particularly at low frequencies, <100 Hz. Also, the magnetopause spectrum usually has a nearly constant slope on a log-log plot across the entire frequency range, whereas the magnetosheath spectrum often has a change in

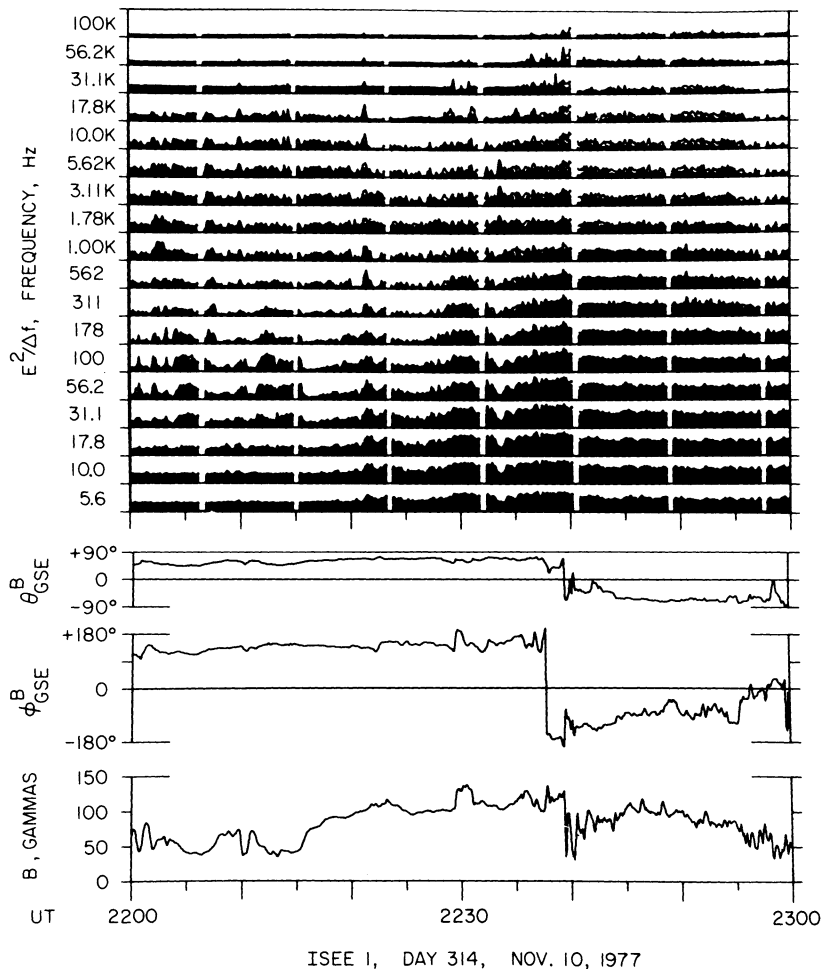


Fig. 5. A detailed comparison of the plasma wave electric and magnetic field intensities and the UCLA magnetic field data for the outbound magnetopause crossing in Figure 1. The magnetic field directions  $\phi_{GSE}^B$  and  $\theta_{GSE}^B$  are in geocentric solar ecliptic coordinates.

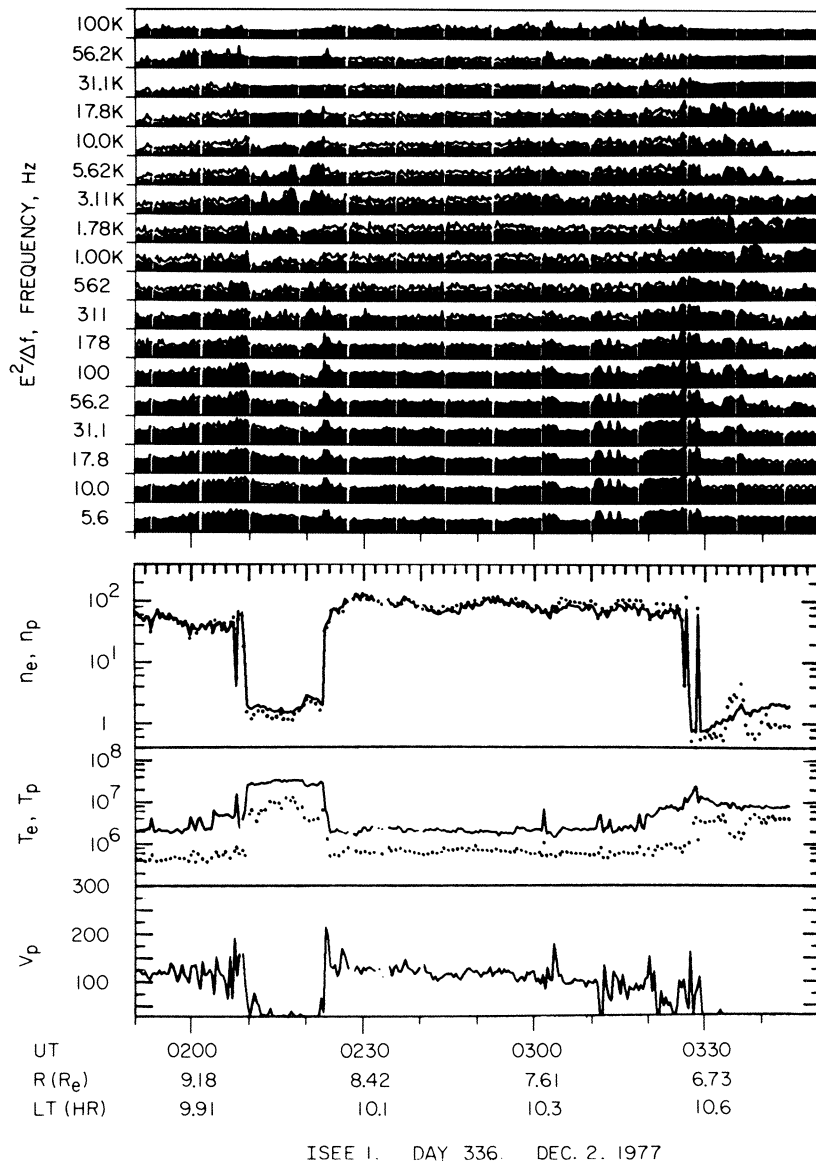


Fig. 6. A series of magnetopause crossings in the local morning on December 2, 1977, again showing enhanced plasma wave electric and magnetic field intensities in the region near the magnetopause.

slope at about 300 Hz, causing a distinct hump in the spectrum at about this frequency. These differences in spectral characteristics are illustrated in Figure 11, which shows selected spectra from the magnetosheath, magnetopause, and magnetosphere for the magnetopause crossing at 1447 UT in Figure 3. As can be seen, the magnetopause electric field spectrum is clearly the most intense and is readily distinguished from the spectra in the magnetosheath and magnetosphere, primarily because of the very nearly linear (power law) frequency dependence on the log-log plot. Usually the magnetosheath and magnetospheric spectra show discrete narrow-band features at intermediate frequencies which deviate considerably from a power law spectrum.

Further details of the fine structure of the electric field spectrum at the magnetopause are shown by the frequency-time spectrograms in Figure 12, which correspond to the magnetopause crossing shown in Figure 4. Prior to about 2230 UT, various narrow-band emissions can be seen inside the magnetosphere. The narrow-band emissions in the top frequency

panels, from about 1 to 3 kHz, are electrostatic waves at frequencies slightly above the local electron cyclotron frequency, and the emissions in the bottom frequency panels, from about 100 to 300 Hz, are electromagnetic whistler-mode chorus emissions [Tsurutani and Smith, 1974, 1977].

In the magnetosheath and near the magnetopause the electric field spectrum is almost featureless, decreasing in intensity with increasing frequency. Many closely spaced spikes can be seen in the spectrum on time scales of a few seconds. These spikelike fluctuations are probably responsible for the large ratio of peak-to-average field strengths evident in Figure 10. The enhanced electric field strengths at the magnetopause are not as evident in Figure 12 as in Figure 4 because of the automatic gain control used in the wideband telemetry system.

In addition to the broad bandwidth electrostatic noise, moderately intense narrow-band electrostatic emissions are occasionally detected near the local electron plasma frequency. Two spectra illustrating these types of emissions, shown in Figure 13, were selected from the outbound magnetopause



crossing on November 10, shown in Figures 4 and 5. Comparisons with the electron density computed from the plasma measurements show that the frequencies of these emissions are very close to the local electron plasma frequency,  $f_p^-$ . These narrow-band emissions are almost certainly due to either electron plasma oscillations at  $f_p^-$  or electrostatic waves near the upper hybrid resonance frequency  $f_{UHR}$ . For the conditions usually encountered,  $f_g^- \ll f_p^-$ , the electron plasma frequency and upper hybrid resonance frequency,  $f_{UHR} = [(f_g^-)^2 + (f_p^-)^2]^{1/2}$ , are so close together that it is not possible to distinguish between these two types of waves. Electrostatic emissions near the electron plasma frequency are frequently observed at the magnetopause, particularly in the region near the magnetopause current layer, as in Figure 5. Other examples of these emissions can be identified in the 31.1- and 56.2-kHz channels of Figure 1 at about 1500 UT (see also Figure 10) and in the 10.0- and 17.8-kHz channels of Figure 8 from about 0803 to 0806 UT. When these emissions occur, they are usually moderately intense, with field strengths ranging from about  $100 \mu\text{V m}^{-1}$  to  $1 \text{ mV m}^{-1}$ , and often occur in extremely short bursts, sometimes lasting only a few tenths of a second.

#### Polarization

In principle it is possible to obtain the polarization of the plasma wave electric fields from the spin modulation of the

electric field intensity. In most cases studied, little or no spin modulation is evident in the electric field turbulence observed near the magnetopause. The low frequency of occurrence of spin modulation effects can be attributed in part to the large fluctuations which are present in this region, thereby making it difficult to clearly identify any spin modulation effects which may be present, and to the low probability of having the magnetic field oriented in a favorable direction for detecting sharp spin modulation nulls. However, a few cases were found in which spin modulation was clearly evident. Whenever a well-defined spin modulation was detected, the electric field was found to be oriented perpendicular to the local magnetic field. These observations are consistent with the low occurrence of spin modulation effects, since for this polarization, sharp nulls can be detected only when the magnetic field is oriented very nearly parallel to the spin plane of the electric antenna, which occurs relatively infrequently.

A good example showing sharp nulls in the electric field intensity is shown in Figure 14. This example is for the magnetopause crossing at about 1447 UT in Figure 3. This illustration shows the electric field intensities in the 100-Hz channel on a time scale which clearly resolves the 3-s rotation of the spacecraft. As is expected, two nulls are observed per rotation. The vertical arrows in Figure 14 indicate the times at which the electric antenna is parallel to the projection of the magnetic field onto the spin plane of the antenna. During this pe-

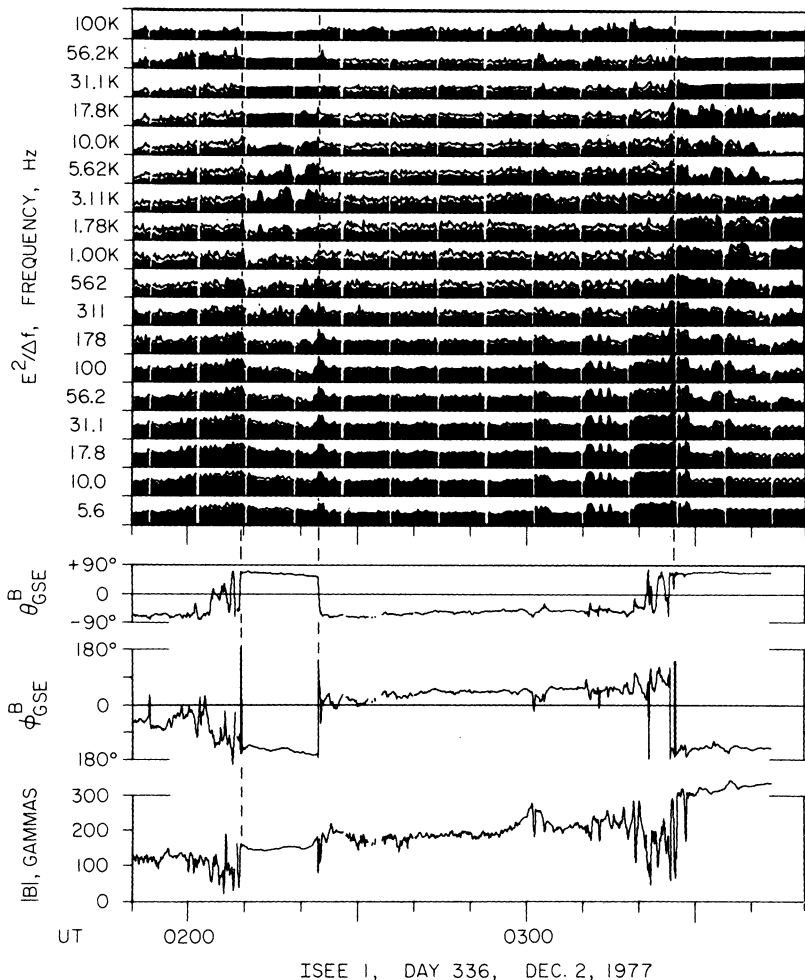


Fig. 7. Detailed plasma wave electric field and UCLA magnetic field data for the magnetopause crossings in Figure 6.

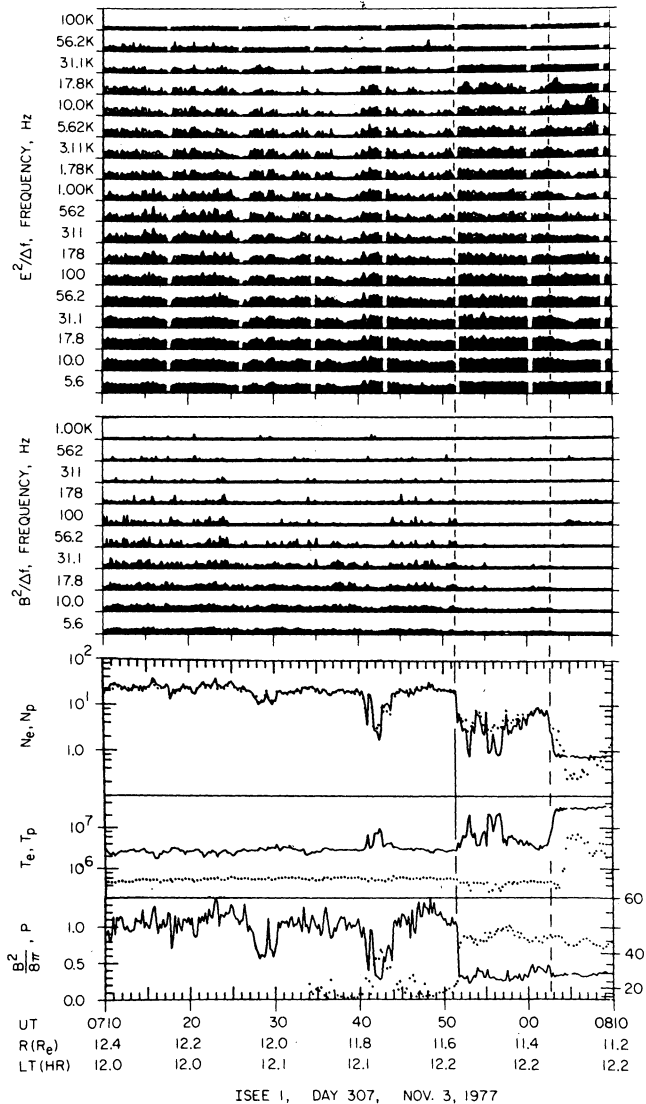


Fig. 8. A magnetopause crossing near local noon showing a long extended boundary layer region from 0751:30 to 0802:45 UT. The boundary layer is characterized by enhanced broad-band electric field intensities, but only a very small increase in the low-frequency magnetic field intensities.

riod the magnetic field direction is only about  $10^\circ$  above the spin plane. The arrows therefore indicate times when the antenna is approximately parallel to the magnetic field. As can be seen, the nulls in the electric field intensity occur almost exactly when the antenna axis is aligned parallel to the magnetic field, thereby confirming that the electric field is perpendicular to the magnetic field. The depth of the nulls, sometimes as much as 20 dB, shows that the electric field is aligned very nearly perpendicular to  $\mathbf{B}$ , probably to within less than  $5^\circ$ . Other crossings have been found giving similar results for frequencies ranging from about 30 Hz to 1 kHz. One important consequence of these polarization measurements is that the electric field polarization provides a clear distinction between the magnetopause electric field turbulence and the electrostatic noise in the magnetosheath. *Rodriquez* [1979] has clearly shown that the magnetosheath electrostatic noise is polarized with the electric field parallel to the magnetic field.

Attempts have also been made to determine the electric field direction of the narrow-band electrostatic emissions near

the electron plasma frequency. Such a determination would be very important, since it would allow us to distinguish electron plasma oscillations, which should have the electric field parallel to  $\mathbf{B}$ , from upper hybrid resonance waves, which should have the electric field perpendicular to  $\mathbf{B}$ . Unfortunately, the very rapid temporal variations and short duration of these emissions have precluded a definitive determination of the electric field direction. Further efforts will be made in the future to determine the polarization of these waves.

### Wavelength

Estimates of the approximate wavelength of the electric field turbulence observed at the magnetopause are important both to help identify the plasma wave mode involved and to evaluate the effects of Doppler shifts on the electric field spectrum. Although wavelengths cannot be determined directly with the ISEE plasma wave instrumentation, some limits on the possible wavelengths can be established by comparing the electric field strengths measured with different antenna lengths. If waves are present with wavelengths shorter than the longest antenna used, then substantial differences should be observed in the electric field intensities, the longer antenna indicating a smaller field strength. If the electric field strengths are in good agreement, then the wavelengths must be substantially longer than the longest antenna.

To investigate the wavelength of the magnetopause electric field turbulence, comparisons have been made between the 215-m tip-to-tip ( $y$  axis) electric antenna on ISEE 1 and the 30-m tip-to-tip ( $x$  axis) electric antenna on ISEE 2. Since these comparisons involve spacecraft separation distances of up to 500 km, crossings must be carefully selected to avoid large temporal variations in the electric field structure during the time between the crossings. To minimize the effects of temporal variations, the approach taken is to find crossings which have a very similar electric field intensity profile on both ISEE 1 and 2, preferably including a relatively broad region of nearly constant intensity. One such example which has been chosen for analysis is the period of enhanced electric field intensity from about 0320 to 0325 UT on December 2, 1977, in Figure 6. During this crossing a very similar electric field intensity profile can be identified on ISEE 2 at a slightly earlier time, from about 0311 to 0316 UT, in good agreement with the transit time determined from the plasma and magnetic field instruments. For comparison the electric field spectra from ISEE 1 and 2 for these two time intervals are shown in Figure 15. Both the peak and the average electric field spectra have been computed for each spacecraft over the selected time intervals. As can be seen, both the peak and the average electric field spectra from the two spacecraft are in excellent agreement, within about a factor of 2 over most of the frequency range. This close agreement is a strong indication that the wavelengths are substantially longer than the length of the longest antenna, 215 m, since if wavelengths shorter than the longest antenna were present, then the spectral densities would differ by a large factor, as much as  $(215/30)^2 = 51$  for wavelengths shorter than the 30-m antenna. Only at the relatively high frequencies, above 10 kHz, do differences this large occur.

Although magnetopause crossings sometimes occur with substantial differences in the electric field spectral density at the two spacecraft, a sufficient number of cases have been found with excellent agreement between the spectra at the two

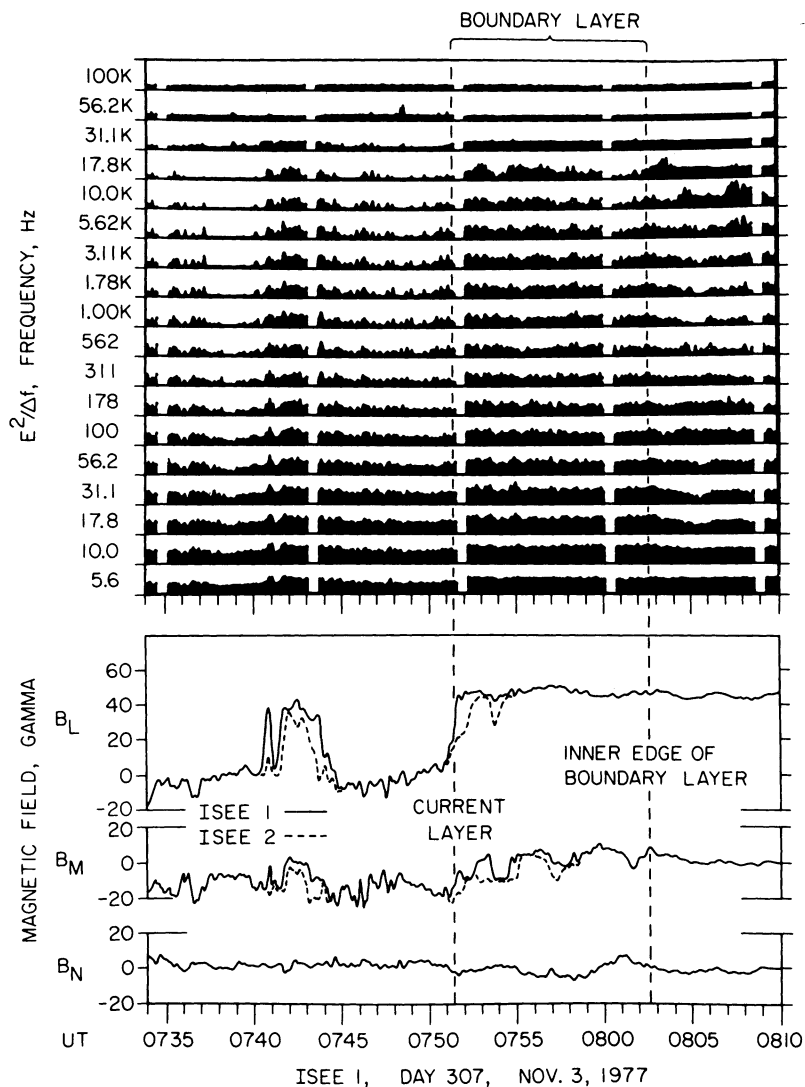


Fig. 9. A detailed comparison of the plasma wave electric field intensities and the UCLA magnetic field data for the magnetopause crossing in Figure 8.

spacecraft to lead us to conclude that these events represent quiescent condition, undisturbed by temporal variations during the time between the two crossings. To the extent that the spectrum in Figure 15 represents a time stationary condition it can be concluded that the wavelength of the electric field turbulence must be substantially longer than 215 m, otherwise larger differences would be observed in the electric field intensities measured by the two antennas. It is possible that wavelengths shorter than 215 m may be present at frequencies above 10 kHz. However, even in this frequency range, limits can be placed on the wavelength because of the Debye length  $\lambda_D = (\epsilon_0 kT/ne^2)^{1/2}$ . As is well known, the shortest wavelength which can occur in a plasma is approximately  $\lambda_m = 2\pi\lambda_D$ . For the case shown in Figure 15 the corresponding electron density and temperatures are  $n_e = 90 \text{ cm}^{-3}$  and  $T_e = 8 \times 10^5 \text{ }^\circ\text{K}$ , which give a Debye length of 6.5 m and a minimum wavelength of about 40 m.

These limitations on the wavelength have important implications with regard to the interpretation of the overall electric

field spectrum of the magnetopause turbulence. Without any information on the wavelengths involved, it would be possible to account for the observed frequency spectrum entirely in terms of Doppler shifts, since the flow velocities near the magnetopause are often very large,  $>100 \text{ km s}^{-1}$ . However, to account for frequencies of 10–100 kHz by Doppler shifts alone, assuming a flow velocity of  $100 \text{ km s}^{-1}$ , would require wavelengths of 1–10 m or less. Since such short wavelengths are not observed and cannot occur because of the Debye length restriction, it seems reasonably certain that the observed spectrum cannot be accounted for by Doppler shifts alone. For wavelengths greater than 200 m and a typical flow velocity of  $100 \text{ km s}^{-1}$  the maximum Doppler shift is less than 500 Hz. At frequencies below about 500 Hz, Doppler shifts could, of course, be very substantial. However, the absence of any break or substantial modification in the shape of the spectrum in this frequency range suggests that Doppler shifts are probably relatively unimportant in determining the overall shape of the spectrum, even at frequencies below 500 Hz.

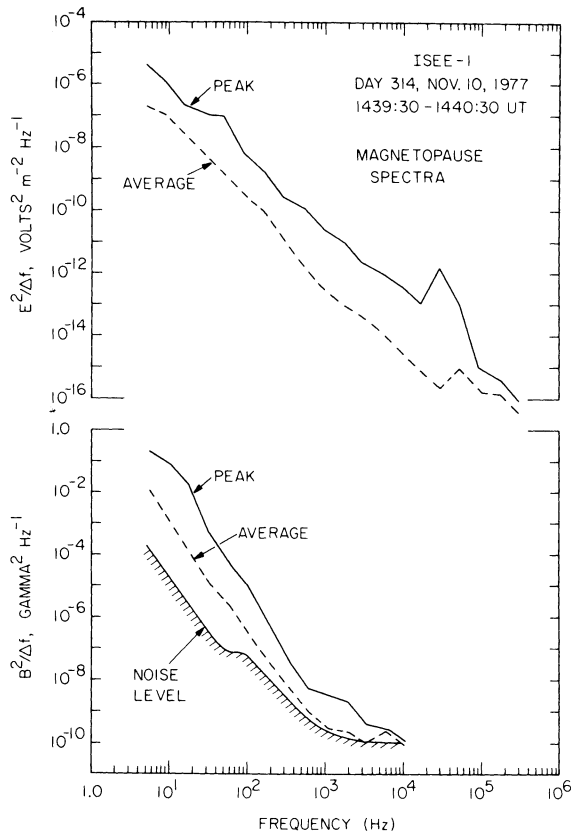


Fig. 10. Typical electric and magnetic field spectra of the enhanced plasma wave turbulence observed near the magnetopause.

#### 4. SUMMARY AND DISCUSSION

In this study we have shown that enhanced plasma wave turbulence levels are a common feature of the magnetopause. Three distinct types of plasma wave noise are observed at the magnetopause, (1) a broad-band spectrum of electric field turbulence extending from a few hertz to about 100 kHz, (2) a broad-band spectrum of magnetic field turbulence extending from a few hertz to about 1 kHz, and (3) less frequently, narrow-band electrostatic emissions near the local electron plasma frequency. Both the broad-band electric field noise and the broad-band magnetic field tend to occur in the same region. Usually the enhanced broad-band electric and magnetic noise intensities occur in a region which corresponds closely to the plasma boundary layer, being bounded by the abrupt magnetic field transition at the magnetopause current layer and the abrupt drop in the plasma density at the inner, earthward, edge of the plasma boundary layer. Comparable electric and magnetic noise intensities have also been observed in regions which *Russell and Elphic* [1979] identify as 'flux transfer events' and in regions which *Paschmann et al.* [1979] identify as either isolated inclusions of plasma into the magnetosphere or a sudden switch-on of the boundary layer. The regions of enhanced plasma wave turbulence levels are nearly always associated with large fluctuations in the plasma flow velocity and density and irregularities in the magnetic field direction and magnitude, all of which are well-known characteristics of the boundary layer plasma. Typical maximum broad-band electric and magnetic field intensities in the

boundary layer, integrated over the frequency range from 5.6 Hz to 311 kHz, are about  $5 \text{ mV m}^{-1}$  and 1 gamma. Because of the steep spectrum, most of the contribution to these broad-band field strengths occurs at low frequencies, so the field strengths would be even larger if the integration were extended to even lower frequencies. In all cases where definitive measurements could be made, for frequencies less than 1 kHz, the electric field is found to be oriented very nearly perpendicular to the local magnetic field, and the wavelengths are longer than about 215 m. The region of occurrence of the narrow-band electrostatic waves near  $f_p^-$  is less certain, since these events do not occur very frequently. In most cases these emissions tend to occur near the magnetopause current layer or in regions with large variations in the magnetic field, indicating large currents. The electric field polarization of these narrow-band emissions could not be determined because of their rapid fluctuations and short duration.

In considering the origin of the broad-band electric field noise, probably the most important characteristic which must be considered is the very broad, nearly featureless, electric field spectrum. Normally, no distinctive narrow-band features or cutoff can be identified in the spectrum which could provide a definite association with a specific plasma wave mode. Because of the very large plasma flow velocities in the region where this noise is observed, it is likely that Doppler shifts

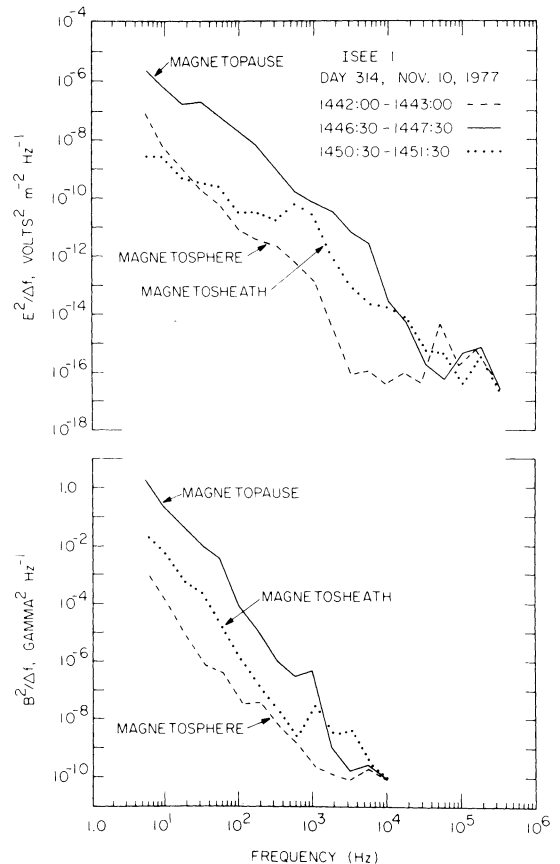


Fig. 11. A comparison of the electric and magnetic field spectra in the magnetosheath, magnetopause boundary layer, and magnetosphere for the magnetopause crossing at 1447 UT in Figure 3. The electric and magnetic field spectra at the magnetopause are clearly distinguished from the magnetosheath and magnetosphere by their increased intensity, particularly at low frequencies.

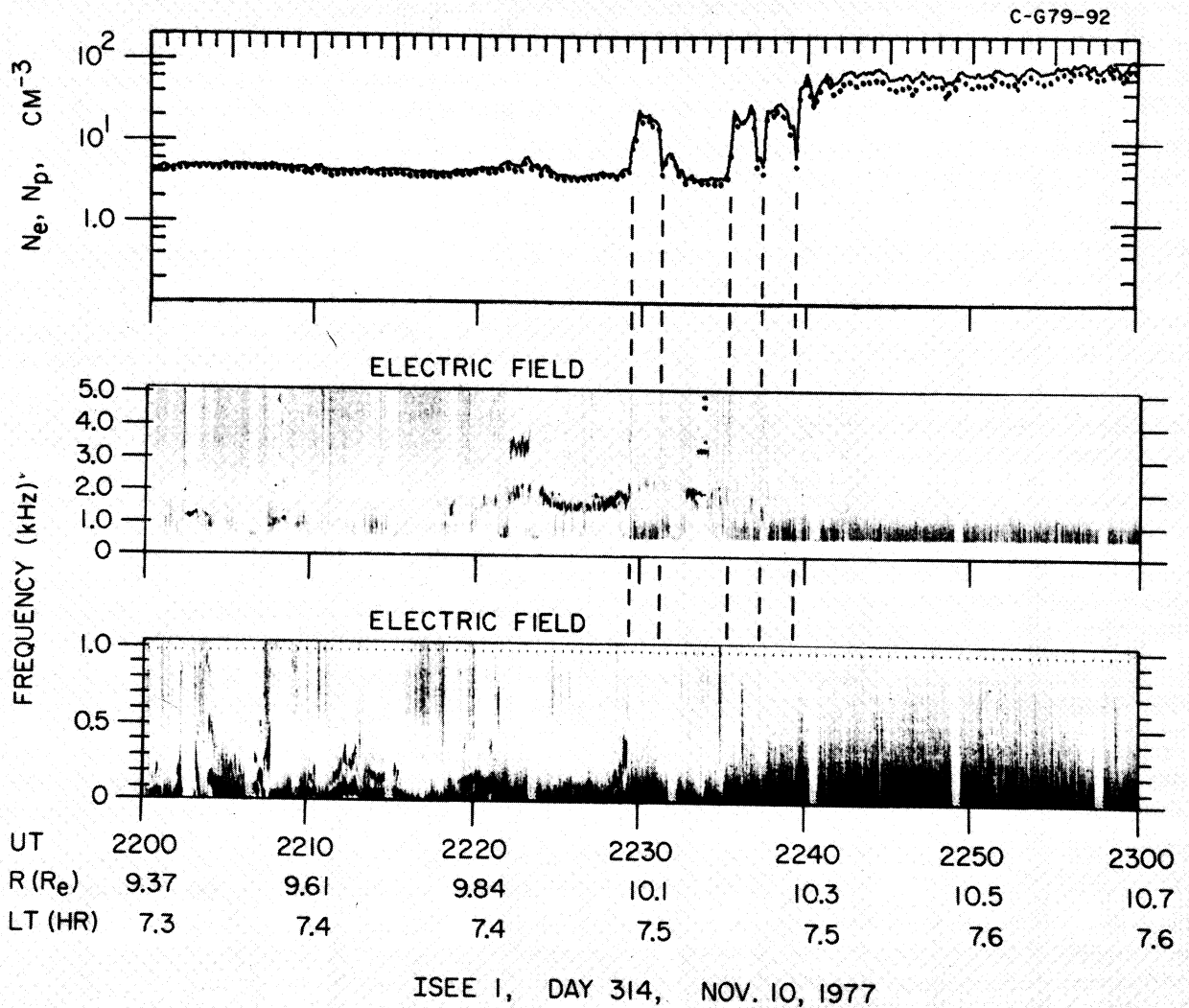


Fig. 12. High-resolution frequency-time spectrograms of the electric field turbulence observed for the magnetopause crossing in Figure 4.

may be present which could smear out sharp narrow-band features in the spectrum. At frequencies below 10 kHz the maximum Doppler shift which would be consistent with the wavelength estimates is about 500 Hz. Overall, the monotonic power law frequency variation of the electric field spectrum gives one the strong impression that this noise represents a fully developed turbulence process with the electric field energy cascading to higher and higher frequencies (larger wave numbers) because of nonlinear interactions.

Because magnetic noise is always observed in the same region as the broad-band electric field noise, the question naturally arises whether the electric field noise is due to electrostatic or electromagnetic waves. The magnetic field noise must consist of whistler-mode waves, since no other electromagnetic mode of propagation occurs in the frequency range, between the proton and the electron gyrofrequencies, where this noise is observed. If the electric field noise consists of whistler-mode waves, then the electric-to-magnetic field energy density ratio must be equal to the square of the whistler-mode index of refraction  $(cB/E)^2 = n^2$ , where  $n$  is the index of refraction. Since the whistler-mode index of refraction squared,  $n^2 = (f_p^-)^2 / f_g^-$ , varies as  $1/f$ , the energy density ra-

tio should vary as  $1/f$ . At low frequencies,  $\approx 1$  kHz, the energy density ratio for the spectra in Figure 10 has approximately the correct frequency dependence,  $(cB/E)^2 \propto 1/f^{1.1}$ , to be consistent with the whistler mode. However, the index of refraction computed from the energy density ratio is about a factor of 10 too small when it is compared with the square of the whistler-mode index of refraction. For example, at 10 Hz,  $cB/E \approx 94$ , whereas the whistler-mode index of refraction using  $f_p^- = 50$  kHz and  $f_g^- = 3.4$  kHz is 270. This comparison indicates that a substantial electrostatic component is present, above what would be expected for whistler-mode waves. It is possible that this additional electric field could be accounted for by whistler-mode waves propagating with wave vectors near the resonance cone, which tends to increase the  $cB/E$  ratio. At higher frequencies,  $>1$  kHz, substantial electric field intensities still exist at frequencies above the electron gyrofrequency,  $f_g^- \sim 3.3$  kHz, in a region of the spectrum where the whistler mode cannot propagate. Since Doppler shifts are believed to be small, it is clear that this portion of the spectrum cannot be accounted for by whistler-mode waves. Because a substantial discrepancy is also present in the electric-to-magnetic field ratio at low frequencies and the elec-

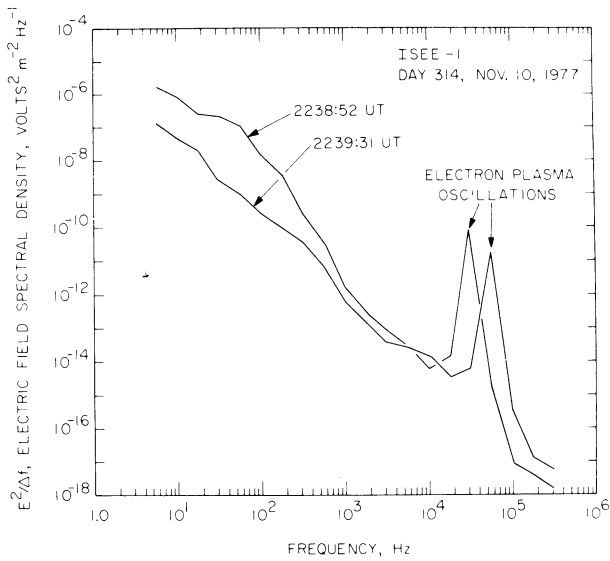


Fig. 13. Selected electric field spectra from the magnetopause crossing in Figures 4 and 5 showing the occurrence of intense narrow-band emissions near the local electron plasma frequency.

tric field spectrum extends smoothly across the whistler-mode resonance at  $f_g^-$ , it seems almost certain that a substantial contribution to the electric field spectrum is due to electrostatic waves, even at frequencies below  $f_g^-$ .

Broad-band electrostatic noise spectra comparable with those in Figure 10 have been observed before in the magnetotail [Gurnett *et al.*, 1976], along the auroral field lines [Gurnett and Frank, 1977], and in the polar cusp regions of the magnetosphere [Gurnett and Frank, 1978]. All of these observations can be interpreted as involving boundary-layer-like plasmas involving substantial currents and spatial gradients not dissimilar to the plasma observed in the magnetopause boundary layer. In all cases where spin modulation measurements have been made, the electric field of the broad-band electrostatic

noise has been found to be oriented very nearly perpendicular to the local magnetic field, similar to the results of this study. The fact that the electric field, hence wave vector  $\mathbf{K}$ , is nearly perpendicular to the local magnetic field and the low electron-to-ion temperature ratio  $T_e/T_i \approx 1$  strongly limits the possible plasma wave modes which could be involved in the generation of this turbulence. At the present time, only two plasma wave instabilities have been identified which could possibly account for the observed characteristics of this turbulence. These instabilities are the electrostatic ion-cyclotron instability [Ashour-Abdalla and Thorne, 1977; Swift, 1977] and the lower-hybrid-drift instability [Huba *et al.*, 1978; Lemon and Gary, 1977]. Both of these instabilities involve wave vectors nearly perpendicular to the magnetic field and are driven by currents parallel to the magnetic field in the case of the ion-cyclotron instability and perpendicular to the magnetic field in the case of the lower-hybrid-drift instability. The lower-hybrid-drift instability also requires a gradient in the plasma density perpendicular to the magnetic field. Both density gradients and currents parallel and perpendicular to the magnetic field are thought to be present in the magnetopause boundary layer, so both of these instabilities are good candidates for explaining the broad-band electrostatic noise observed in this region. The absence of distinct lines near the ion-cyclotron frequency or the lower-hybrid-resonance frequency is probably not a serious concern because Doppler shifts and non-linear effects could act to broaden the spectrum and smear out these identifying features. Since the ion-cyclotron frequency is very small,  $f_g^- \sim 1$  Hz, in the region where the broad-band electrostatic noise is observed, only a small Doppler shift would be required to convert discrete emissions at high harmonics of the ion-cyclotron frequency into an essentially continuous spectrum. One possible difficulty with the ion-cyclotron mechanism is that extremely high harmonics of the ion-cyclotron frequency would have to be excited to explain the broad bandwidth of the electrostatic noise. If the main energy input to the turbulence spectrum occurs at the lower-hybrid resonance frequency,  $f_{LHR} \approx (f_g^- f_g^+)^{1/2}$ , then one would

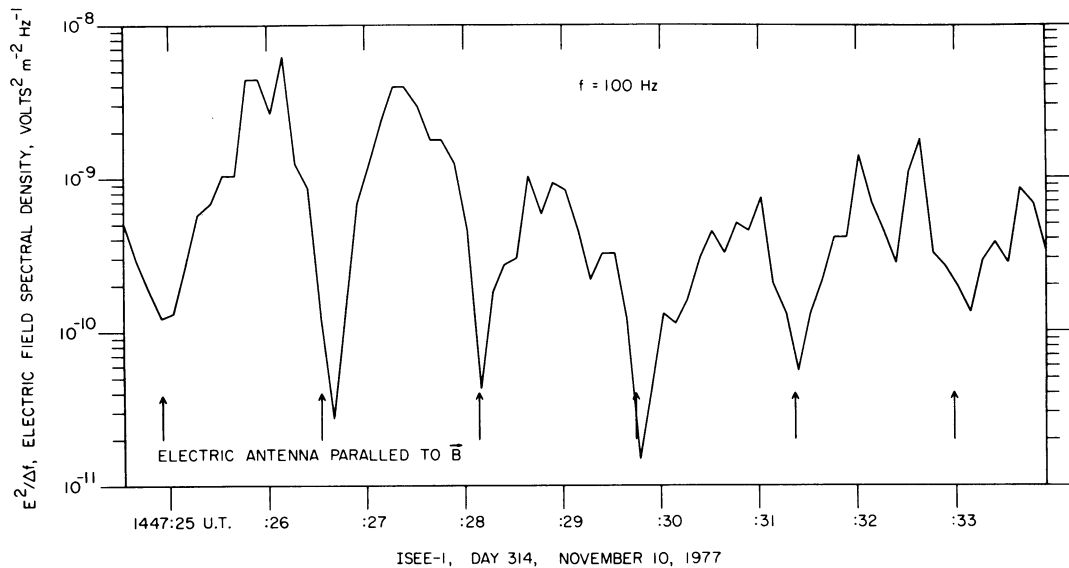


Fig. 14. High time resolution electric field measurements at 100 Hz for the magnetopause crossing at 1447 UT in Figure 3 showing the occurrence of sharp spin modulation nulls. The nulls occur when the electric antenna axis is oriented approximately parallel to the local magnetic field, indicating that the electric field of the broad-band electrostatic turbulence is polarized perpendicular to the magnetic field.

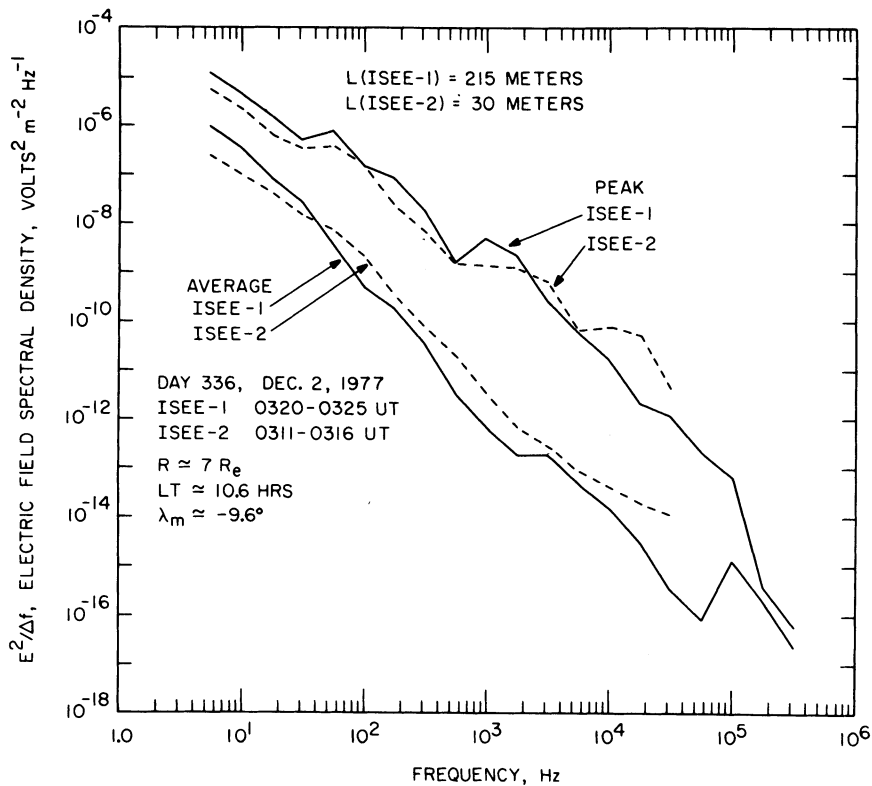


Fig. 15. A comparison of the spectrum of the magnetopause electric field turbulence using the 215-m electric dipole antenna on ISEE 1 and the 30-m electric dipole antenna on ISEE 2. The close agreement between the two spectra at frequencies below about 10 kHz, indicates that the turbulence has wavelengths substantially longer than 215 m in this frequency range.

expect some indication of this characteristic frequency in the observed electric field spectra. In some cases, such as the spectrum at 2238:52 UT in Figure 13, a distinct break in the slope of the spectrum can be seen at about 50 Hz, which is near the lower-hybrid-resonance frequency. However, many other cases occur, such as in Figure 10 and 15, for which the slope of the spectrum is essentially constant in the region near  $f_{LHR}$ .

The origin of the whistler-mode magnetic noise observed in the magnetopause boundary layer involves similar interpretational problems. Since energetic,  $>2$  keV, electron fluxes comparable with the energy spectra typical of the outer magnetosphere are detected in these regions [Russell and Elphic 1979], one possibility is that the whistler-mode turbulence is generated by an anisotropy in the energetic electron flux, with a greatly enhanced growth rate caused by the reduced resonance velocity in the relatively dense cool boundary layer plasma, as in the mechanism of Kennel and Petschek [1966]. However, inspection of the electron anisotropy in the region where the whistler-mode magnetic noise is observed usually does not indicate a sufficient anisotropy to produce whistler-mode growth over such a broad frequency band. The steeply decreasing magnetic field spectrum, with maximum intensities below a few hertz, suggests instead that the origin of this turbulence occurs at low frequencies, the higher frequencies being produced by a nonlinear cascade process. Several mechanisms based on velocity shear [D'Angelo, 1973] and drift wave instabilities exist which could account for the generation of the turbulence.

Before the origin of the narrow-band emissions near the electron plasma frequency can be established the electric field

polarization must be determined. If the electric field is parallel to the local magnetic field, then the waves are probably electron plasma oscillations driven unstable by field-aligned electron beams. Attempts have been made to identify such electron beams in the plasma data without success, possibly owing to the extremely short duration,  $<1$  s, of the plasma oscillation bursts. If the electric field polarization is perpendicular to the local magnetic field, then the waves are probably associated with the upper-hybrid-resonance frequency and similar to the intense upper-hybrid waves reported by Christiansen *et al.* [1978] and Gurnett *et al.* [1979]. These waves are commonly observed in the outer regions of the magnetosphere, and their origin has been investigated in some detail by Rönmark *et al.* [1979] and Kurth *et al.* [1979].

Having considered the possible origins of the plasma wave turbulence observed at the magnetopause, the principal and probably most important question which remains is the possible effect which this turbulence may have on the overall structure of the magnetopause. The existence of greatly enhanced plasma wave turbulence levels at the magnetopause strongly indicates that microscopic plasma processes play an important role in this region of the magnetosphere. The possibilities are numerous. The broad-band electrostatic turbulence may provide the anomalous resistivity required to account for the magnetopause energy dissipation and heating reported by Mozer *et al.* [1979] and Scudder and Ogilvie [1979]. This turbulence may account for the acceleration of electrons to high energies in the region near the magnetopause, as discussed by Meng and Anderson [1975] and Baker and Stone [1978]. Electric and magnetic turbulence may play

a role in the spatial diffusion and transport of charged particles across the magnetopause. For the moment we do not attempt to answer these basic theoretical questions. The main intent of this paper is to provide the essential parameters, electric and magnetic field spectra and relationships to plasma and magnetic field characteristics, needed to stimulate further investigation of these important problems.

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