

# Plasma Waves in the Distant Magnetotail

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In this study we identify the principal types of plasma waves which occur in the distant magnetotail, and we investigate the relationship of these waves to simultaneous plasma and magnetic field measurements made on the same spacecraft. The observations used in this study are from the Imp 8 spacecraft, which passes through the magnetotail at radial distances ranging from about 23.1 to 46.3  $R_E$ . Three principal types of plasma waves are detected by Imp 8 in the distant magnetotail: broad band electrostatic noise, whistler mode magnetic noise bursts, and electrostatic electron cyclotron waves. The electrostatic noise is a broad band emission which occurs in the frequency range from about 10 Hz to a few kilohertz and is the most intense and frequently occurring type of plasma wave detected in the distant magnetotail. This noise is found in regions with large gradients in the magnetic field near the outer boundaries of the plasma sheet and in regions with large plasma flow speeds,  $10^3$  km s<sup>-1</sup>, directed either toward or away from the earth. The whistler mode magnetic bursts observed by Imp 8 consist of nearly monochromatic tones which last from a few seconds to a few tens of seconds. These noise bursts occur in the same region as the broad band electrostatic noise, although much less frequently, and are thought to be associated with regions carrying substantial field-aligned currents. Electrostatic electron cyclotron waves are seldom detected by Imp 8 in the distant magnetotail. Although these waves occur very infrequently, they may be of considerable importance, since they have been observed in regions near the neutral sheet when the plasma is extremely hot.

## 1. INTRODUCTION

It is widely recognized that processes occurring in the distant magnetotail are of fundamental importance to the understanding of the interaction of the earth's magnetosphere with the solar wind. The intense plasma heating which takes place in the plasma sheet region of the magnetotail is usually attributed to the merging of oppositely directed magnetic fields at one or more  $x$  type neutral lines, with the subsequent conversion of magnetic field energy into kinetic energy [Dungey, 1961; Axford *et al.*, 1965; Speiser, 1965]. Although the overall configuration of the magnetic fields and plasmas in the magnetotail is reasonably well understood, the detailed microscopic processes which occur in this region and their relationship to auroras and substorms are not. Classical magneto-hydrodynamics requires a finite conductivity in the merging region. Since the plasma is essentially collisionless, an important question arises as to how this finite conductivity can occur. Piddington [1967], Dungey [1972], Syrovatskii [1972], and others have suggested that plasma wave turbulence produces an anomalous resistivity in the merging region and thereby provides the mechanism for dissipating the magnetic field energy. Similar plasma wave turbulence processes are thought to occur in regions of field-aligned currents associated with auroral precipitation [Kindel and Kennel, 1971]. The sudden onset of enhanced plasma wave turbulence, either in the

merging region or along the auroral field lines, has been suggested as the triggering mechanism for magnetospheric substorms [Piddington, 1967]. On the other hand, turbulence free processes have also been suggested to explain the merging process and the triggering of auroral substorms [Schindler, 1974]. Because of the possible role of plasma waves in these processes it is of considerable general interest to investigate the plasma wave phenomena which occur in the distant magnetotail.

At the present time, few plasma wave observations have been reported in the plasma sheet and neutral sheet regions of the distant magnetotail. Using data from the Ogo 1, 3, and 5 satellites, which provide measurements only in the near-earth regions of the plasma sheet (at radial distances  $R \lesssim 17 R_E$ ), Brody *et al.* [1968] have reported observations of brief bursts of whistler mode magnetic noise near the neutral sheet. Early electric field measurements on Ogo 5 by F. L. Scarf revealed no VLF electric field oscillations in the tail with the exception of substorm-associated waves in the near-earth plasma sheet at radial distances of less than 12  $R_E$  [Russell, 1972]. More recently, Scarf *et al.* [1974], using measurements from the Imp 7 spacecraft at a radial distance of about 30  $R_E$ , have reported observations of moderately intense electric field oscillations in the region immediately outside the plasma sheet and very intense (160 mV) low-frequency magnetic noise in the high-density region of the plasma sheet.

The purpose of this paper is to present the results of an extensive study of plasma waves in the distant magnetotail using measurements from the Imp 8 spacecraft. These plasma wave measurements are compared with plasma and magnetic

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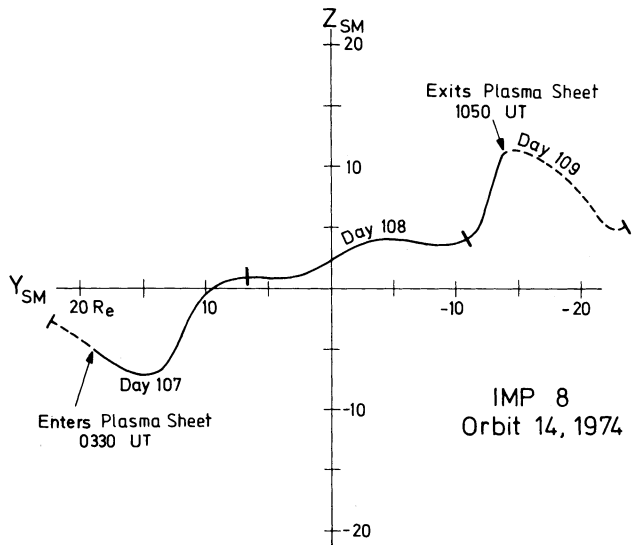


Fig. 1. Solar magnetospheric coordinates  $Y_{SM}$  and  $Z_{SM}$  for the magnetotail pass on days 107, 108, and 109, 1974. During this pass,  $X_{SM}$  varies from about  $-23.4$  to  $-35.6 R_E$ .

field measurements presented in a companion paper by Frank *et al.* [1976] to study the relationship of the plasma waves to the various plasma regimes found in the distant magnetotail.

## 2. SPACECRAFT ORBIT AND INSTRUMENTATION

All of the measurements employed in this study were obtained with instrumentation on the Imp 8 (Explorer 50) spacecraft. This spacecraft is in a low-eccentricity orbit with initial perigee and apogee geocentric radial distances of 23.1 and 46.3  $R_E$ , respectively, and an orbit inclination of  $41.5^\circ$  with respect to the ecliptic plane. Because of the large orbit inclination, Imp 8 provides essentially complete coverage in 1 year of a cross section of the magnetotail at distances of about 25–35  $R_E$  from the earth. Approximately 20 passes occur through the magnetotail each year. However, of these, only about 6 or 7 passes provide crossings of the neutral sheet. For this study we have examined all of the plasma wave data, and selected portions of the plasma and magnetic field data, for a 15-month period from December 22, 1973, to March 22, 1974. These data include a total of 26 passes through the magnetotail of which 8 have clearly defined neutral sheet crossings.

Measurements are shown from three instruments on Imp 8, the University of Iowa plasma wave experiment, the University of Iowa low-energy proton and electron differential energy analyzer (Lepedea), and the Goddard Space Flight Center (GSFC) magnetometer. The plasma wave experiment on Imp 8 provides electric field measurements from 40 Hz to 2.0 MHz and magnetic field measurements from 40 Hz to 1.78 kHz. Electric field measurements are obtained by using a 'long' (121.5 m from tip to tip) electric dipole antenna which is extended outward perpendicular to the spacecraft spin axis. The spin axis is oriented perpendicular to the ecliptic plane. Magnetic field measurements are obtained by using a triaxial search coil magnetometer. Further details of the Imp 8 plasma wave experiment are given by Gurnett [1974].

The Lepedea on Imp 8 provides measurements of the differential energy spectrums and angular distributions of protons and electrons over the energy range 50 eV to 45 keV. Electron and proton energy spectrums are obtained in 16 energy passbands and in 16 directions (sun-sectored) for each passband.

The Lepedea also includes a Geiger-Mueller tube which is sensitive to electrons with energies  $E \geq 45$  keV and protons with energies  $E \geq 650$  keV. The fields of view of both the Lepedea and the Geiger-Mueller tube are oriented perpendicular to the spacecraft spin axis. Further details of the Lepedea instrumentation are given by Frank *et al.* [1976].

The magnetometer on Imp 8 is a triaxial flux gate magnetometer with a range of about  $\pm 36 \gamma$  and a resolution of 0.3  $\gamma$ . Further details of this instrument are given by Scarce *et al.* [1976].

## 3. A TYPICAL IMP 8 PASS THROUGH THE NEUTRAL SHEET

To illustrate the general features of the Imp 8 plasma wave measurements, we first discuss a representative pass through the neutral sheet. The solar magnetospheric coordinates  $Y_{SM}$  and  $Z_{SM}$ , for this pass, which occurred on days 107, 108, and 109, 1974, are shown in Figure 1. Both the plasma and the magnetic field data, which are discussed later, show that the spacecraft enters the plasma sheet at about 0330 UT on day 107 and leaves the plasma sheet at about 1050 UT on day 109. This pass was selected for discussion because the magnetic field data show a very clear transition from the southern to the northern lobes of the magnetotail with an extended period (on day 108) in the vicinity of the neutral sheet.

The magnetic field and plasma wave measurements obtained during this pass are shown in Figures 2, 3, and 4. The corresponding plasma data for this pass are shown in Plates 1, 2, and 3. The top panels of Figures 2, 3, and 4 show the magnetic field measurements from the GSFC magnetometer, and the middle and bottom panels show the plasma wave magnetic and electric field intensities. The angles  $\theta_{SM}^B$  and  $\varphi_{SM}^B$  of the magnetic field direction are given in solar magnetospheric coordinates, and the magnetic field magnitude is in gammas. The plasma wave magnetic field intensities are shown in seven frequency channels from 40 Hz to 1.78 kHz, and the electric field intensities are shown in 15 frequency channels from 40 Hz to 178 kHz. The ordinate for each channel is proportional to the logarithm of the field strength, with a range of 100 dB from the base line of one channel to the base line of the next higher channel. The vertical bars plotted for each channel give the average field strengths, averaged over intervals of 163.8 s, and the dots give the peak field strengths.

The magnetic field data show that after the spacecraft enters the plasma sheet at about 0330 UT on day 107 (Figure 2) it is located in the southern lobe of the magnetotail, with the magnetic field directed away from the sun ( $\varphi_{SM}^B \approx 180^\circ$ ). The spacecraft remains in the southern lobe of the magnetotail with a relatively steady magnetic field of about 15–20  $\gamma$  until about 0200 UT on day 108 (Figure 3). Starting at this time and continuing for the next 24 hours until about 0230 UT on day 109 (Figure 4), the magnetic field magnitude undergoes a series of depressions and directional changes which indicate multiple encounters and crossings of the neutral sheet. After about 0230 UT on day 109 and until the spacecraft leaves the plasma sheet at about 1050 UT the magnetic field is directed toward the sun ( $\varphi_{SM}^B \approx 0^\circ$ ) with a relatively steady magnitude of about 20  $\gamma$ , indicating that the spacecraft is in the northern lobe of the magnetotail.

Several types of plasma waves are evident in the magnetotail during this pass. In the electric field channels above about 50 kHz, many sporadic bursts of auroral kilometric radiation are evident throughout the pass (see Figure 2). Since this type of radiation is generated close to earth [Gurnett, 1974] and does

not interact with the plasma in the distant magnetotail, it will not be considered further in this paper. This radiation does, however, provide a useful index of auroral and magnetospheric substorm activity.

At lower frequencies, from about 5 to 50 kHz, a nearly steady level of continuum radiation is present for the entire duration of the pass through the magnetotail. As has been shown by *Gurnett and Shaw* [1973], this radiation is permanently trapped in the low-density regions of the magnetospheric cavity at frequencies below the solar wind plasma frequency. The abrupt cutoff of the trapped continuum radiation at the magnetopause crossings on days 107 and 109 is clearly evident in the 10.0- and 16.5-kHz channels. In the inner regions of the magnetosphere the low-frequency cutoff of the trapped continuum radiation is at the local electron plasma frequency,  $f_p$ , and can be used to make very accurate determinations of the local electron density [*Gurnett and Frank*, 1974]. It was initially thought that this cutoff could be used to determine the electron density in the very low density high-latitude regions of the magnetotail, where it is very difficult to measure the plasma density with other techniques. However, as was shown by this pass and by detailed analysis of many other passes, the low-frequency cutoff of the continuum radiation is essentially constant, independent of the spatial position within the magnetotail. The cutoff must therefore be determined by the plasma frequency in the source (or somewhere else in the magnetosphere) and not by the local plasma frequency. Since this radiation is also thought to be generated relatively close to the earth [*Gurnett*, 1975], this noise will not be discussed further in this paper.

In the region near the neutral sheet on day 108 (Figure 3), many intense bursts of low-frequency (40 Hz to 1.78 kHz) electric field noise are observed. This type of noise is detected on all passes which come close to the neutral sheet region and is the most intense type of plasma wave detected by Imp 8 in the distant magnetotail. Because the spectrum of this noise extends over a very broad frequency range and because no comparable noise is detected by the magnetic field sensor, we refer to this noise as broad band electrostatic noise. The detailed characteristics of this noise are discussed in section 4.

Another type of plasma wave is also evident in the low-frequency (40–562 Hz) magnetic field channels in Figure 3. This noise occurs much less frequently than the broad band electrostatic noise and is most clearly evident in the peak measurements, indicating that the noise consists of many short bursts. Since this noise is detected by a magnetic antenna and occurs at frequencies below the electron gyrofrequency, which is typically a few hundred hertz in these regions, the noise must consist of whistler mode waves. We refer to this noise as whistler mode magnetic noise bursts. The detailed characteristics of these magnetic noise bursts are discussed in section 5.

The one remaining type of plasma wave observed by Imp 8 in the distant magnetotail consists of electrostatic waves near harmonics of the electron gyrofrequency. Waves of this type are frequently observed in inner regions of the magnetosphere [*Kennel et al.*, 1970] and are called electron cyclotron waves. Electron cyclotron waves of this type are seldom observed in the distant magnetotail and did not occur during the pass illustrated in Figures 2, 3, and 4. The detailed characteristics of this noise are discussed in section 6.

#### 4. BROAD BAND ELECTROSTATIC NOISE

The pass illustration in Figures 2, 3, and 4 provides an excellent example of the typical characteristics of the broad

band electrostatic noise detected by Imp 8. The noise usually occurs over a broad range of frequencies extending from about 10 Hz to 1 kHz and with intensities ranging from about  $50 \mu\text{V m}^{-1}$  to  $5 \text{ mV m}^{-1}$ . A typical spectrum of this noise, selected during an interval of relatively high intensity, from 1056 to 1059 UT on day 108, is shown in Figure 5. These electric field spectral densities are computed from the average field strength measurements and assume that the effective length of the electric antenna is one half of the tip-to-tip length. The rms electric field amplitude, integrated from 40 Hz to 10 kHz, is about  $1.23 \text{ mV m}^{-1}$  in this case. The peak electric field strengths for this same interval are about a factor of 3–5 times larger than the average field strengths. Usually, the intensity of the broad band electrostatic noise is less than that shown in Figure 5. However, on every pass close to the neutral sheet, several intervals of half an hour or more are usually encountered with intensities comparable to those in Figure 5.

To illustrate the fine structure of the broad band electrostatic noise, a high-resolution frequency-time spectrogram of this noise is shown in Figure 6. Two different frequency scales are shown to provide good resolution over the entire frequency range. The spectrum of the broad band electrostatic noise is seen to consist of many discrete bursts lasting from a few seconds to several minutes. These bursts often have a characteristic V shaped frequency-time variation, first decreasing and then increasing in frequency with increasing time. The spectrum also shows a marked decrease in intensity at frequencies above about 400 Hz. This upper cutoff frequency agrees well with the local electron gyrofrequency  $f_g^-$ , which varies from about 400 to 500 Hz during the interval shown in Figure 6. Some weak bursts do, however, extend up to frequencies of several kilohertz, well above the electron gyrofrequency. This same quasi-cutoff effect near the electron gyrofrequency is evident in the spectrum of Figure 5, where the electron gyrofrequency was about 300 Hz. The wide band spectrograms in Figure 6 also show a well-defined lower cutoff frequency at about 10 Hz. This low-frequency cutoff is believed to correspond to the local lower hybrid resonance frequency  $f_{LHR}$ . If  $f_p^- \gg f_g^-$ , which is usually the case in the regions where this noise is observed, the lower hybrid resonance frequency is given by  $f_{LHR} = (f_g^- f_g^+)^{1/2}$  [*Stix*, 1962]. For the spectrum in Figure 6,  $(f_g^- f_g^+)^{1/2}$  varies from about 10.5 to 11.6 Hz (assuming that the ions are protons).

To help establish the mode of propagation of the broad band electrostatic noise, it is useful to determine the orientation of the electric field relative to the static magnetic field. The direction of the electric field in the plane of rotation of the electric antenna can be obtained from the spin modulation of the noise intensity. To provide a meaningful interpretation in terms of the local magnetic field direction, measurements of this type must be made when the magnetic field lies close to the plane of rotation of the antenna. Fortunately, for the case shown in Figure 6 the magnetic field is in a satisfactory direction ( $\varphi_{SE}^B \approx 165^\circ$  and  $\theta_{SE}^B \approx 5^\circ$ ) for this type of analysis. Because the intensity of the noise fluctuates considerably, the intensity must be sector averaged over many rotations to determine the modulation pattern. The spin modulation observed for the event in Figure 6, averaged from 1037 to 1106 UT, is illustrated in Figure 7. These data show that a very distinct null occurs when the electric antenna axis is parallel to the local magnetic field. The depth and angular position of the null indicate that the electric field must be oriented within about  $\pm 20^\circ$  from perpendicular to the magnetic field.

To clearly establish the region of the magnetotail in which

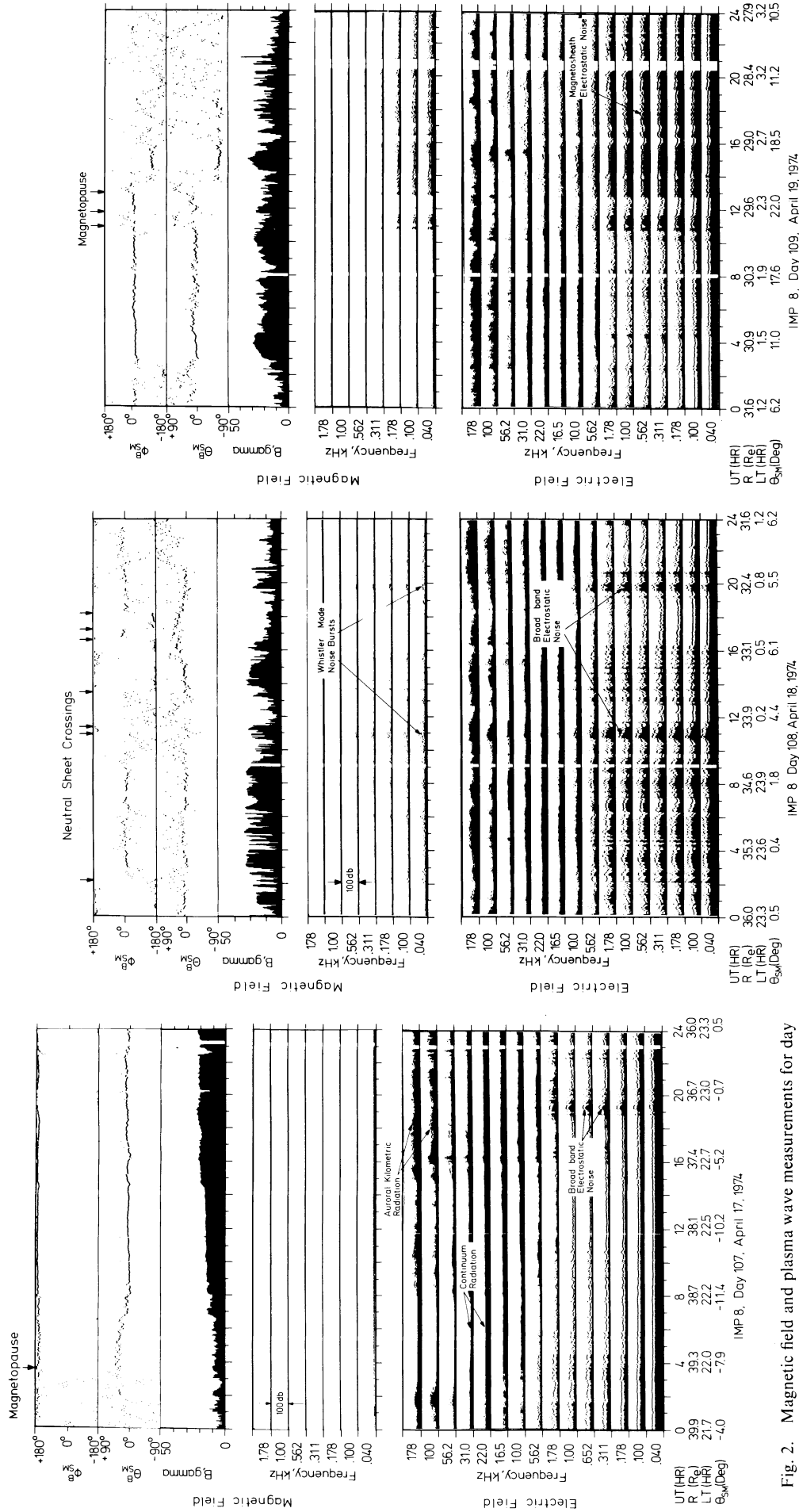


Fig. 2. Magnetic field and plasma wave measurements for day 107. After entering the plasma sheet at about 0330 UT the spacecraft is in the southern lobe of the magnetotail ( $\Theta_{SM} \approx \pm 180^\circ$ ). In the high-frequency electric field channels, many sporadic bursts of auroral kilometric radiation and a nearly constant level of continuum radiation are present throughout this pass. At lower frequencies, several brief periods of intense broad band electrostatic noise are evident near the end of the day, at about 1930 and 2230 UT.

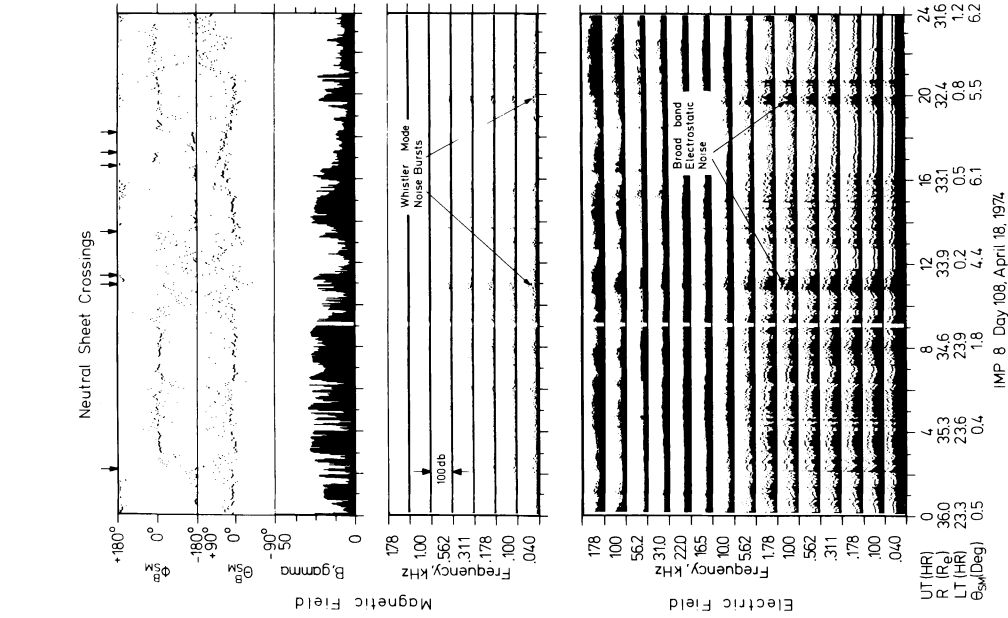


Fig. 3. Continuation of the measurements in Figure 2 for day 108. During most of this day the spacecraft is within the plasma sheet, and several clearly defined crossings of the neutral sheet are evident. Many intense bursts of broad band electrostatic noise and several intervals with whistler mode magnetic noise bursts occur in this region.

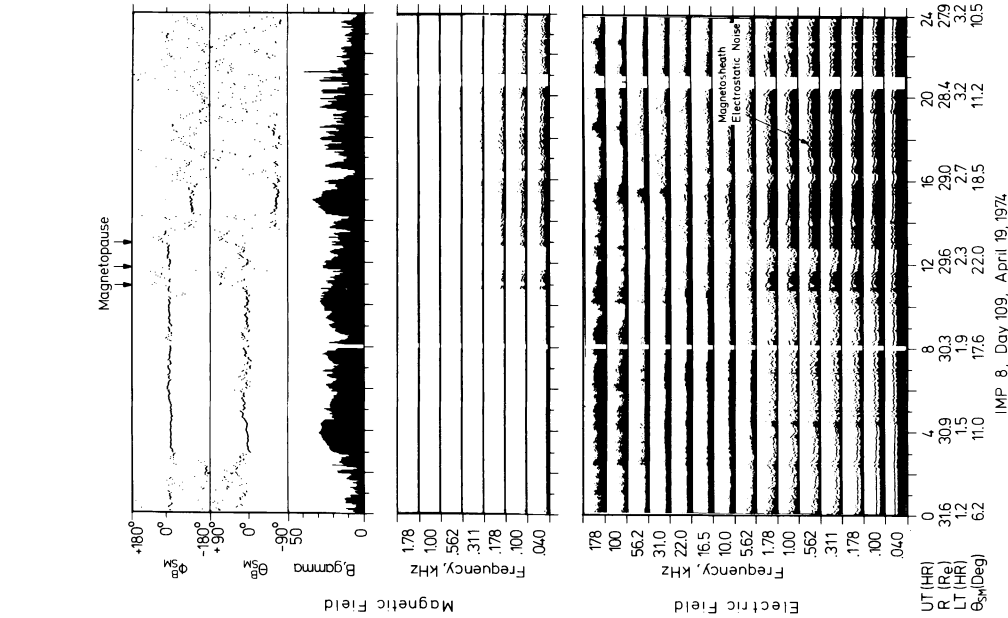


Fig. 4. Continuation of the measurements in Figure 3 for day 109. After about 0200 UT until the exit from the plasma sheet at about 1050 UT the spacecraft is in the northern lobe of the magnetotail. The plasma wave intensities in this region are quite low, comparable to the intensities in the southern lobe of the magnetotail in Figure 2.

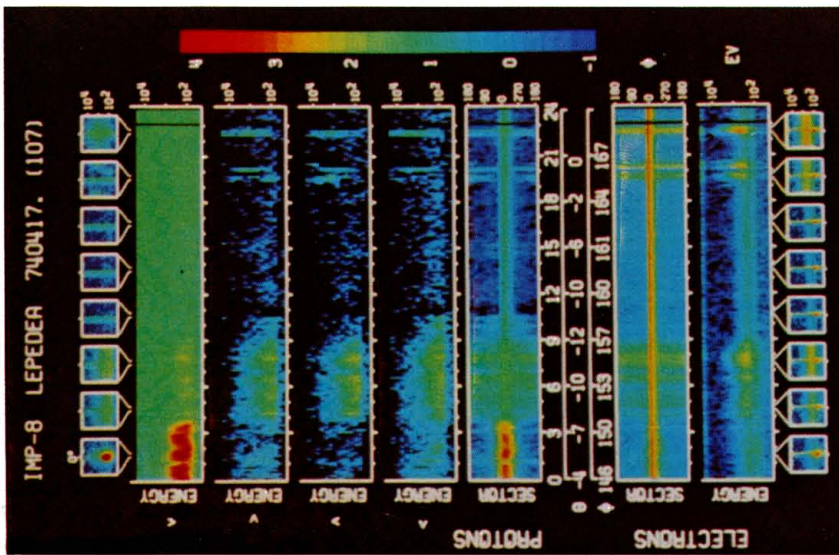


Plate 1. Lapedea observations for day 107. The corresponding plasma wave data are shown in Figure 2. Entry into the plasma sheet is clearly indicated by the change in the proton energy spectrum and angular distribution at about 0330 UT. The broad band electrostatic noise at about 1930 UT occurs in a region of intense sunward proton flow (see the proton sector spectrogram at this time).

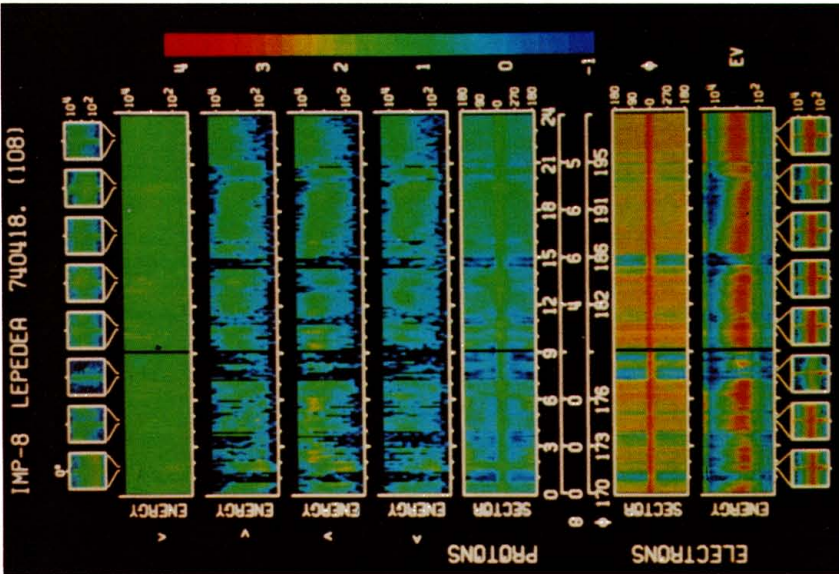


Plate 2. Lapedea observations for day 108. The corresponding plasma wave data are shown in Figure 3. The intense broad band electrostatic noise present from about 0200 to 1200 UT occurs in a region of sporadic sunward proton flow near the boundary of the plasma sheet. In the more isotropic regions deeper within the plasma sheet, from 1700 to 1900 UT and from 2100 to 2400 UT, for example, the broad band electrostatic noise is completely absent.

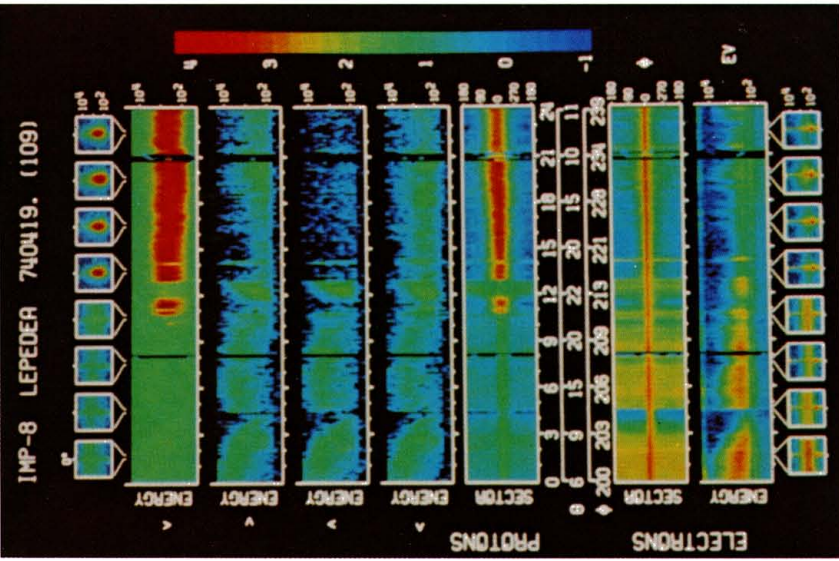


Plate 3. Lapedea observations for day 109. The corresponding plasma wave data are shown in Figure 4. The spacecraft remains in the nearly isotropic high-density region of the plasma sheet with very little plasma wave activity until the satellite's exit from the plasma sheet at about 1050 UT.

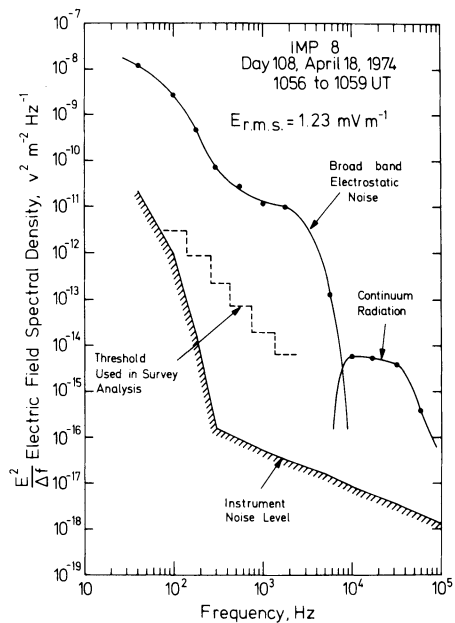


Fig. 5. A typical spectrum of the broad band electrostatic noise during a period of relatively high intensity, from 1056 to 1059 UT on day 108. The electron gyrofrequency during this period is about 300 Hz.

the broad band electrostatic noise is most frequently observed, we have analyzed all of the available Imp 8 magnetotail passes to determine the frequency of occurrence of this noise as a function of  $Y_{SM}$  and  $Z_{SM}$ . To compute the frequency of occurrence, events are counted only when the electric field spectral density simultaneously exceeds the thresholds indicated by the dashed lines in Figure 5. The results of this analysis are shown in Figure 8. It is evident that the broad band electrostatic noise is observed over a very broad region of the magnetotail. The

largest frequency of occurrence is clearly in the region near the neutral sheet; however, the noise is often detected at distances of as much as 10–15  $R_E$  from the neutral sheet. Comparisons of individual events with switches in the magnetic field direction between  $\varphi_{SM}^B \approx 0^\circ$  and  $\varphi_{SM}^B \approx 180^\circ$  clearly show that although the broad band electrostatic noise occurs in the general region near the neutral sheet, it is not uniquely associated with crossings of the neutral sheet.

To identify the plasma region associated with the broad band electrostatic noise, the Lepedea data have been investigated on several selected passes through the neutral sheet. To illustrate the relationships typically observed, the Lepedea data for the pass discussed earlier, on days 107, 108, and 109 of 1974, are shown in Plates 1, 2, and 3. The details of these spectrogram displays of the Lepedea data are given in the companion paper by Frank *et al.* [1976]. In summary, the top four panels of each plate give (from top to bottom) the energy spectrums of protons in four viewing directions, toward the sun, toward local evening, away from the sun, and toward local morning, and the bottom panel gives the energy spectrum of electrons averaged over all sectors. The panels labeled 'sector' give the angular distributions of protons and electrons averaged over all energies.

In comparing the plasma measurements with the broad band electrostatic noise intensities, several relationships are apparent. First, the noise is usually observed near the boundaries of the plasma sheet. For example, many crossings of the plasma sheet boundary are evident from about 1900 UT on day 107 to about 1600 UT on day 108, and the broad band electrostatic noise intensity is correspondingly very large during this period. The noise intensity variations often show a very clear relationship to brief encounters with the plasma sheet, as from 1900 to 2000 UT and from 2215 to 2345 UT on day 107. Normally, the noise is completely absent in the very low density ( $\sim 0.01$  protons  $\text{cm}^{-3}$ ) regions characteristic of the high-latitude magnetotail and in the high-density regions deep

### ELECTRIC FIELD SPECTRUM

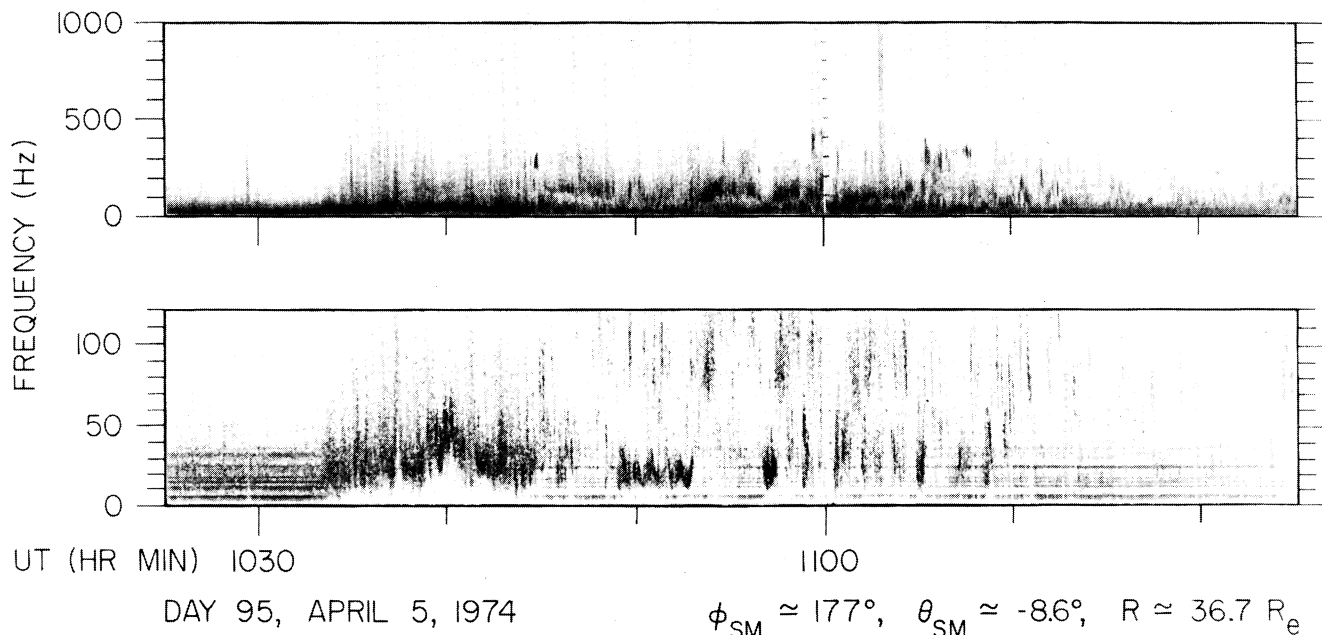


Fig. 6. Frequency-time spectrogram of the broad band electrostatic noise. Note the low-frequency cutoff at about 10 Hz and the marked decrease in the intensity above about 400 Hz. The electron gyrofrequency during this period varies from about 400 to 500 Hz.

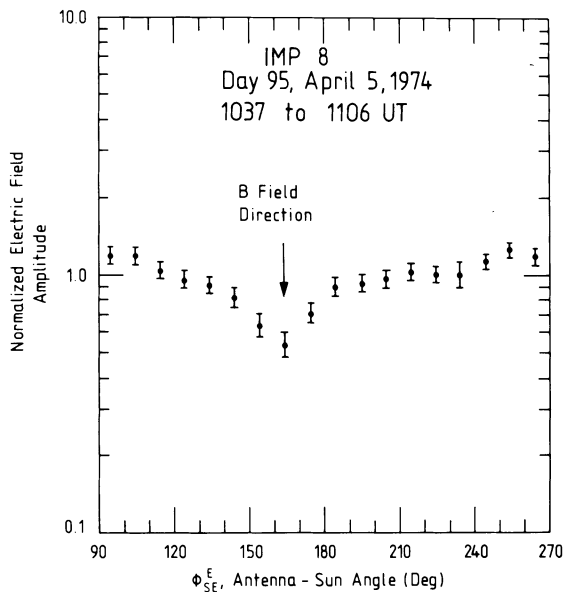


Fig. 7. Normalized electric field amplitude as a function of antenna orientation angle for the broad band electrostatic noise shown in Figure 6. The null in the electric field amplitude occurs when the antenna axis is approximately parallel to the local magnetic field.

within the plasma sheet. For example, when an extended period of several hours occurs where little or no plasma can be detected, as from about 1100 to 1900 UT on day 107, the noise intensities are very low. Similarly, when the spacecraft is within the high-density region of the plasma sheet for an extended period, as from about 1630 to 1900 on day 108, the intensities are very low.

Further evidence of the association of the broad band electrostatic noise with the boundaries of the plasma sheet is provided by the magnetic field data. Usually, the largest broad band noise intensities are observed in regions where large gradients occur in the magnetic field magnitude, particularly as the magnetic field changes from the relatively steady field characteristic of the high-latitude magnetotail to the depressed and more variable field in the plasma sheet. Because of the obvious difficulty in separating temporal variations from spatial variations it is not certain just how far these waves may extend inside or outside the plasma sheet boundaries. Measurements by two spacecraft are needed to eliminate some of these uncertainties.

Second, in most cases the broad band electrostatic noise occurs in regions which have highly anisotropic fluxes of protons streaming either toward or away from the sun, of the type discussed by Frank *et al.* [1976]. A good example of this association occurs from about 1900 to 2000 UT on day 107 in Figure 2. During this interval, which corresponds to a period of enhanced broad band noise intensity, both the proton energy spectrogram viewing away from the sun and the proton sector spectrogram (see Plate 1) show an intense flux of protons with energies of several keV streaming toward the sun. Another example of this relationship occurs during the period of intense broad band noise from about 1900 to 2000 UT on day 108 in Figure 3. As shown by Frank *et al.* [1976, Figure 1] this interval is characterized by substantial plasma flows directed away from the sun with velocities as large as  $600 \text{ km s}^{-1}$ . In comparison, the preceding interval from about 1630 to 1900 UT has very low electric field intensities and correspondingly small flow velocities, less than  $200 \text{ km s}^{-1}$ . The most intense

broad band electrostatic noise encountered during this pass, from about 1045 to 1140 UT on day 108, occurs in a region of very large flow velocities, greater than  $10^3 \text{ km s}^{-1}$ , which Frank *et al.* [1976] identify as the 'fireball,' the region of primary charged particle acceleration in the magnetotail. The maximum electric field intensities in this region, at about 1056 UT, occur essentially coincident with the change in the  $B_z$  component of the magnetic field (solar magnetospheric coordinates) from northward to southward and a corresponding switch in the plasma flow velocity from earthward to tailward [see Frank *et al.*, 1976, Figure 4]. A detailed analysis by Frank *et al.* [1976] of the charged particle angular distributions provides substantial evidence that this region of intense electric field turbulence and large rapidly fluctuating plasma flow velocities represents an encounter with the merging region in the distant magnetotail.

Because of temporal variations associated with auroral substorms it is very difficult to separate temporal variations, such as could occur from the sudden onset of a plasma instability, from variations produced by movements of the plasma sheet boundaries. Simple inspection of the intensity variations of the broad band electrostatic noise strongly suggests that the intensity variations of this noise are often closely associated with temporal variations in auroral activity taking place near the earth. Abrupt increases or changes in the broad band electrostatic noise intensity are often associated with abrupt increases in the intensity of the auroral kilometric radiation generated in the auroral regions near the earth. An example of this type of association is shown in Figure 9 for another Imp 8 pass through the plasma sheet near local midnight. Several distinct periods of enhanced auroral kilometric radiation are evident in the 56.2-, 100-, and 178-kHz channels during this period, the most prominent starting at about 1205, 1830, and 2200 UT. The onset of each of these periods of intense auroral kilometric radiation occurs coincident with an abrupt increase in the intensity of the broad band electrostatic noise. Although this relationship does not always occur on a one-to-one basis,

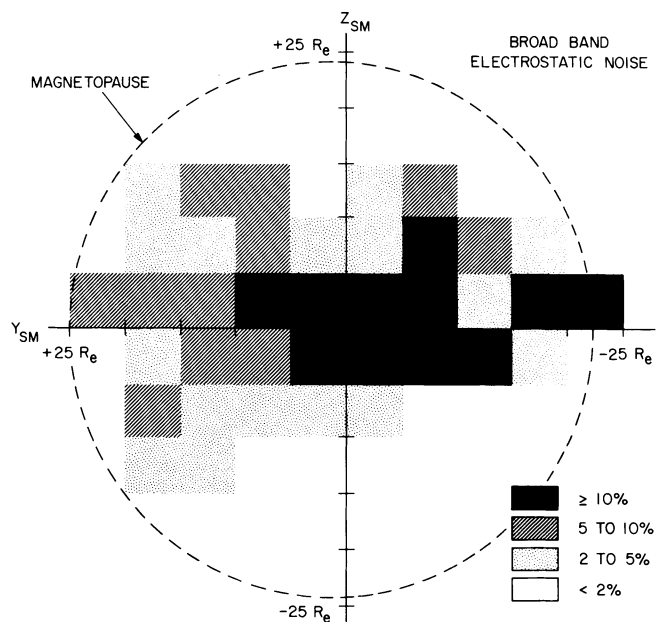


Fig. 8. Frequency of occurrence of the broad band electrostatic noise as a function of  $Y_{SM}$  and  $Z_{SM}$ . The thresholds used for this analysis are shown in Figure 5.

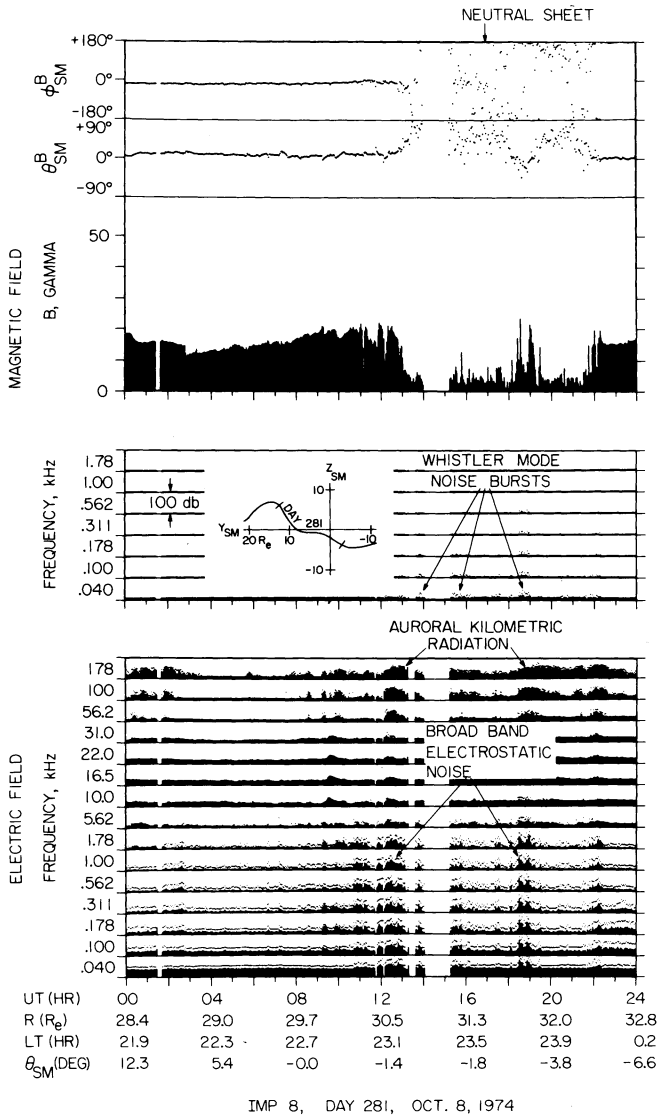


Fig. 9. Example of the association between abrupt increases in the intensity of auroral kilometric radiation generated near the earth (at about 1205, 1830, and 2200 UT in the 56.2-, 100-, and 178-kHz channels) and increases in the intensity of the broad band electrostatic noise in the distant magnetotail. Comparisons of these data with the corresponding plasma measurements of Frank *et al.* [1976, Figure 6] provide further examples of the association of the broad band electrostatic noise with the boundaries of the plasma sheet and with regions of large plasma flow velocities.

it occurs sufficiently often to suggest that the broad band electrostatic noise observed in the distant magnetotail by Imp 8 is closely associated with auroral activity taking place close to the earth.

In comparing the frequency-time spectra of the broad band electrostatic noise (Figure 6) with other types of plasma waves observed in the earth's magnetosphere one is immediately impressed with the close similarity to a type of broad band whistler mode noise called auroral hiss. Until now, auroral hiss has only been observed at low altitudes, up to a few thousand kilometers, over the auroral zone [Gurnett, 1966; Laaspere *et al.*, 1971; Gurnett and Frank, 1972]. Although the frequency range of the auroral hiss observed by low-altitude satellites, about 1–100 kHz, is much different from the frequency range of the broad band electrostatic noise observed in the distant magnetotail by Imp 8, 10 Hz to a few kilohertz,

both types of noise have many characteristics in common. First, although the frequency ranges are quite different, both the auroral hiss and the broad band electrostatic noise occur in the same frequency range,  $f_{LHR} < f < f_B^-$ , relative to the local characteristic frequencies of the plasma. The fact that some weak bursts of broad band electrostatic noise extend above the electron gyrofrequency can be attributed to Doppler shifts caused by the large streaming velocities (up to  $10^3$  km s $^{-1}$ ) observed in the region where the noise is detected. Second, both types of noise are nearly electrostatic, with the electric field oriented approximately perpendicular to the magnetic field. As discussed by Taylor and Shawhan [1974], auroral hiss is propagating in the whistler mode with the wave vector very close to the resonance cone. This wave normal direction results in a quasi-electrostatic type of propagation with a very small wave magnetic field. Because of the quasi-electrostatic mode of propagation, with the wave vector along the resonance cone, the electric field direction of auroral hiss is nearly perpendicular to the local magnetic field over most of the frequency range, similar to the electric field direction of the broad band electrostatic noise. Third, the detailed spectral characteristics of both the auroral hiss and the broad band electrostatic noise have a very similar appearance when the frequency scales are adjusted to account for the different frequency ranges in which these waves are observed. In particular, auroral hiss often has distinct V shaped spectral features, called 'V shaped hiss' and 'saucers' [see Gurnett and Frank, 1972], which bear a close similarity to the V shaped bursts evident in the broad band electrostatic noise. The frequency spectrum of the broad band electrostatic noise detected by Imp 8 in the distant mag-

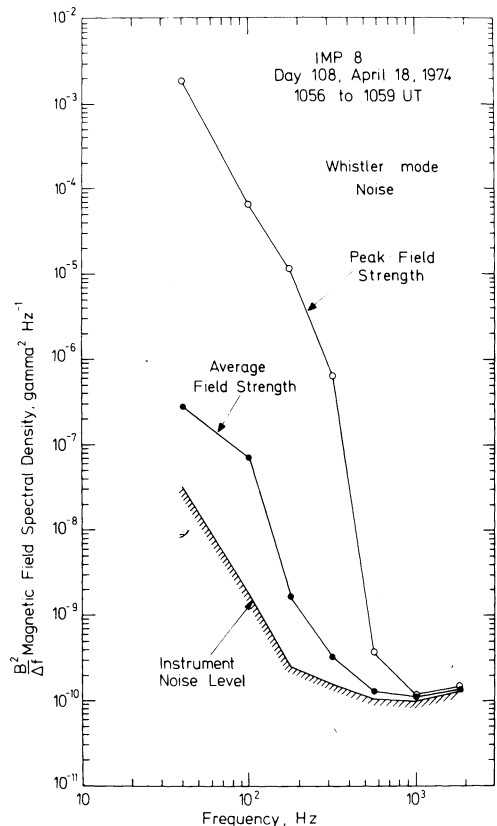


Fig. 10. Typical spectrum of the whistler mode magnetic noise bursts. The large ratio of peak to average field strength indicates that the noise consists of many short but intense bursts.



## MAGNETIC FIELD SPECTRUM

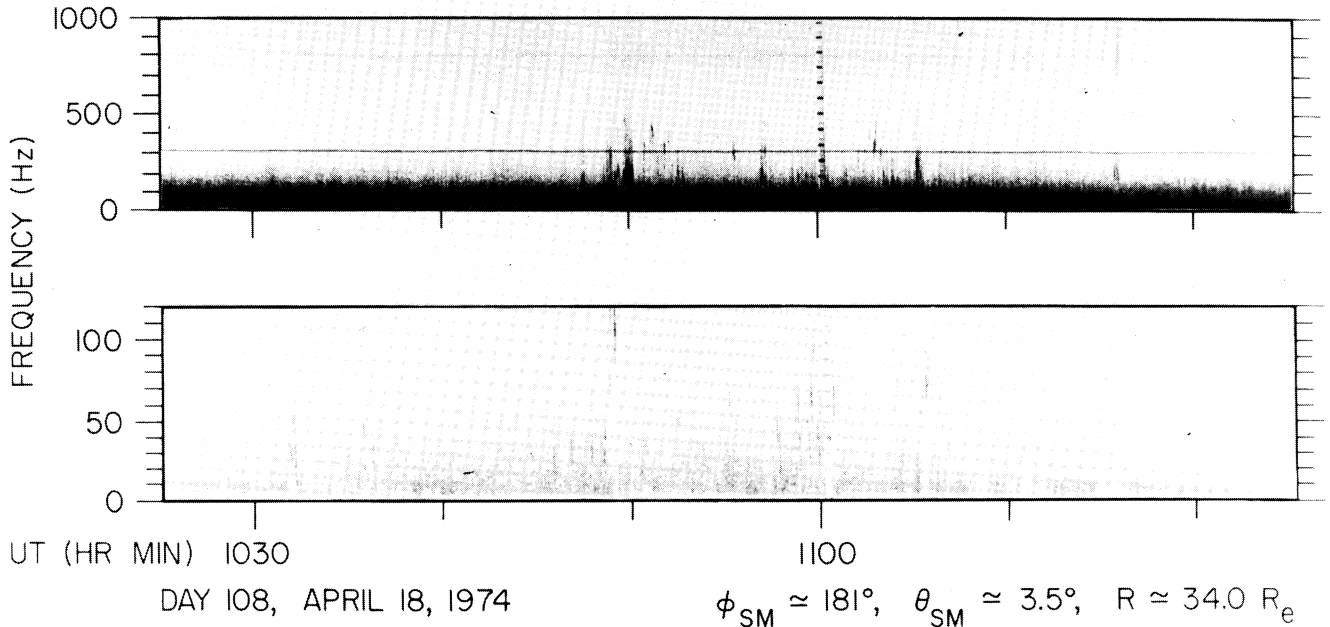


Fig. 11. Frequency-time spectrogram of the whistler mode magnetic noise burst. These bursts consist of many narrow bandwidth tones with rapidly varying frequencies lasting from a few seconds to a few tens of seconds.

netotail also shows a remarkable similarity to the moderately intense electrostatic noise detected throughout the magnetosheath, downstream of the earth's bow shock [Rodriguez and Gurnett, 1975]. The frequency range for the magnetosheath noise, a few hertz to about 1 kHz, is very similar to the frequency range of the broad band electrostatic noise, and the wide band spectrums of the magnetosheath noise have distinct V shaped spectral features which are remarkably similar to the broad band electrostatic noise (compare Figure 12 of Rodriguez and Gurnett [1975] with Figure 6 of this paper).

##### 5. MAGNETIC NOISE BURSTS

During the pass illustrated in Figures 2, 3, and 4, several bursts of noise are evident in the low-frequency (40–311 Hz) magnetic field channels as the spacecraft passes through the region near the neutral sheet on day 108. These bursts are most clearly detected in the peak measurements and are particularly intense at about 0600, 1058, and 2000 UT (see Figure 3). Spectrums of the peak and average magnetic field spectral densities during one of the more intense bursts, from 1056 to 1059 UT, are shown in Figure 10. The peak field strengths are seen to be much larger than the average strengths. For example, the peak magnetic field strength in the 40-Hz channel during this interval is 126 m $\gamma$ , whereas the rms magnetic field strength determined from the average field strength measurements is only 4.6 m $\gamma$ . The large ratio of peak to average field strength indicates that the noise consists of many intense but brief bursts. To illustrate the detailed fine structure of this noise, a wide band frequency-time spectrogram from this same interval is shown in Figure 11. The bursts are seen to consist of nearly monochromatic tones, with rapidly changing frequencies, which last from a few seconds to a few tens of seconds. The frequency range of these bursts is always below the local electron gyrofrequency, which varies between about 300 and 500 Hz for the event shown in Figure 11. Since the only electromagnetic mode of propagation which occurs in this

frequency range is the whistler mode, these bursts are almost certainly propagating in the whistler mode.

Magnetic noise bursts of the type illustrated in Figures 10 and 11 occur much less frequently than the broad band electrostatic noise discussed in the previous section. A few such bursts are, however, observed on essentially every pass which comes close to the neutral sheet. To determine the region of the magnetotail in which these noise bursts are most frequently observed, the frequency of occurrence of this noise has been analyzed in the same way as was done for the broad band electrostatic noise. To compute the frequency of occurrence, any burst exceeding the noise level of any one of the magnetic field channels by more than 2 dB is counted as an event (see Figure 10 for the noise levels of the magnetic field sensor). The results of this frequency of occurrence analysis are shown in Figure 12. It is evident that the magnetic noise bursts occur in a region close to the neutral sheet ( $|Z_{SM}| \lesssim 5 R_E$ ).

Comparison with the magnetic field and plasma data shows that although the magnetic noise bursts occur in the region near the neutral sheet, the bursts do not necessarily occur in the region where the spacecraft actually crosses the neutral sheet. As we have seen for the broad band electrostatic noise, the magnetic noise bursts tend to occur in regions with large gradients in the magnetic field near the boundaries of the plasma sheet. The bursts are often completely absent in regions of very small magnetic field, such as at about 1200 UT on day 108, and in the high-density inner region of the plasma sheet, as from 1600 to 1900 UT and from 2230 to 2400 UT on day 108. Frequently, the magnetic noise bursts are observed in the same region where the broad band electrostatic noise is unusually intense and where magnetic merging is thought to be taking place, for example, at about 1058 UT on day 108. Although it is possible that the weak average field intensities in these regions may be directly associated with the broad band electrostatic noise, the spectrums of these two types of noise are quite different (compare Figures 6 and 11). Thus although

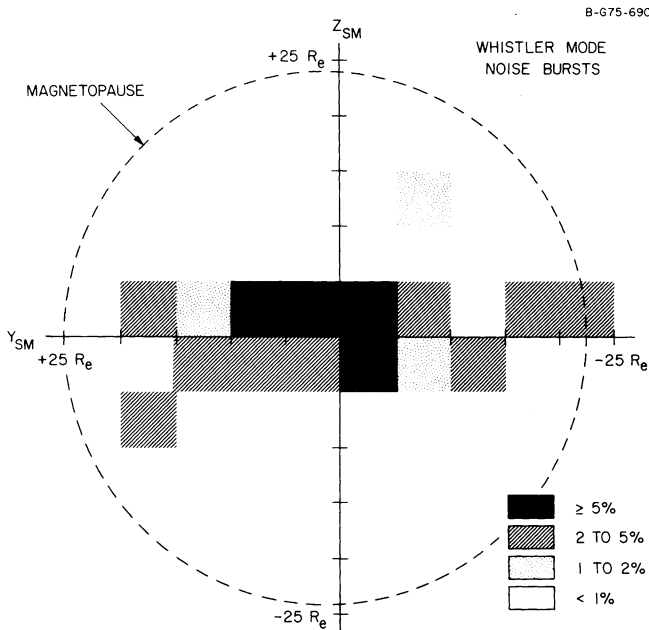


Fig. 12. Frequency of occurrence of the whistler mode magnetic noise bursts as a function of  $Y_{SM}$  and  $Z_{SM}$ . Any burst exceeding the noise level of the magnetic antenna by more than 2 dB is counted in this analysis.

the magnetic noise bursts sometimes occur in the same region as the broad band electrostatic noise, these bursts apparently constitute a completely different type of plasma instability. The electric field of the whistler mode magnetic noise bursts has not been detected, probably because the much more intense broad band electrostatic noise is usually present in the same region.

Although the magnetic noise bursts are observed in the same region and under similar conditions as the broad band electrostatic noise, the characteristics of these two different types of noise are quite different. It seems likely that these two types of noise are produced by distinctly different instability mechanisms, both of which occur for the same type of particle distribution function. The broad band electrostatic noise evidently has a lower instability threshold, since this noise is observed much more frequently and over a broader region than the magnetic noise bursts. Since both types of noise display characteristics of the whistler mode, the main difference is probably the wave normal angle at which the instability occurs. The large magnetic field amplitudes of the magnetic noise bursts are characteristic of whistler mode propagation at wave normal angles parallel to the magnetic field, whereas the large electric field amplitudes of the broad band electrostatic noise are characteristic of propagation at wave normal angles near the resonance cone.

In comparing these observations with previous studies it is almost certain that the magnetic noise bursts detected by Imp 8 are of the same type reported by *Brody et al.* [1968], using measurements from Ogo 1 in the near-earth region of the plasma sheet at radial distances of 15–20  $R_E$  from the earth. The magnetic noise bursts detected by Imp 8 also have spectral characteristics similar to the whistler mode noise bursts called 'lion's roar,' which occur throughout the magnetosheath [*Smith et al.*, 1969]. Although the frequency range and duration of the magnetic noise bursts detected in the magnetotail are similar to lion's roar, the intensity is usually about a factor of 5 smaller.

*Scarf et al.* [1974] have reported observations of continuous high-intensity (160 mV) low-frequency magnetic field noise in the high-density regions of the distant plasma sheet. The brief intense magnetic field bursts discussed in this paper cannot correspond to this nearly continuous noise. Magnetic noise comparable to that discussed by Scarf et al. has not been detected in the distant magnetotail by the University of Iowa plasma wave instruments on either Imp 6 or Imp 8.

## 6. ELECTROSTATIC ELECTRON CYCLOTRON WAVES

The one remaining type of plasma wave detected in the distant magnetotail by Imp 8 consists of narrow band electrostatic emissions near harmonics of the electron gyrofrequency. This type of plasma wave did not occur during the pass illustrated in Figure 1 and has been observed only a few times in all of the available Imp 8 magnetotail data. A case in which this type of noise is observed is shown in Figure 13. During this pass a well-defined crossing from the southern to the northern lobe of the magnetotail takes place from about 0430 to 0440 UT, with  $\varphi_{SM}^B$  switching from 180° to 0°. During this entire period the magnetic field is directed northward, indicating that the spacecraft is on closed field lines within the plasma sheet. Starting at about 0345 UT, slightly before the neutral sheet crossing, and continuing to about 0545 UT, well

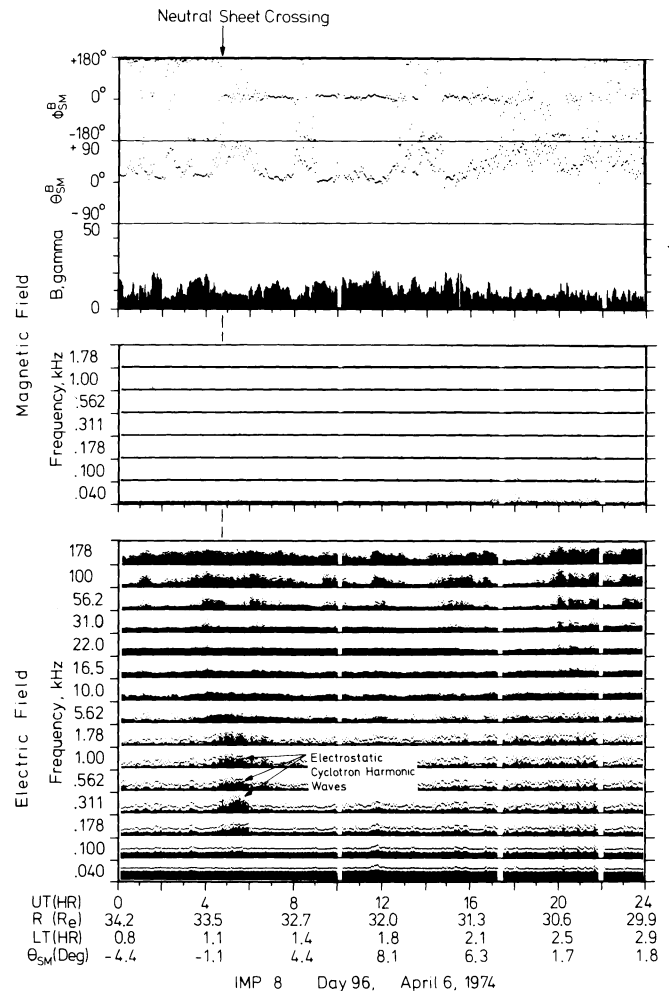


Fig. 13. Magnetic field and plasma wave intensities for a case where electrostatic electron cyclotron waves are observed. This event occurs near a neutral sheet crossing and in a region where the plasma is extremely hot.

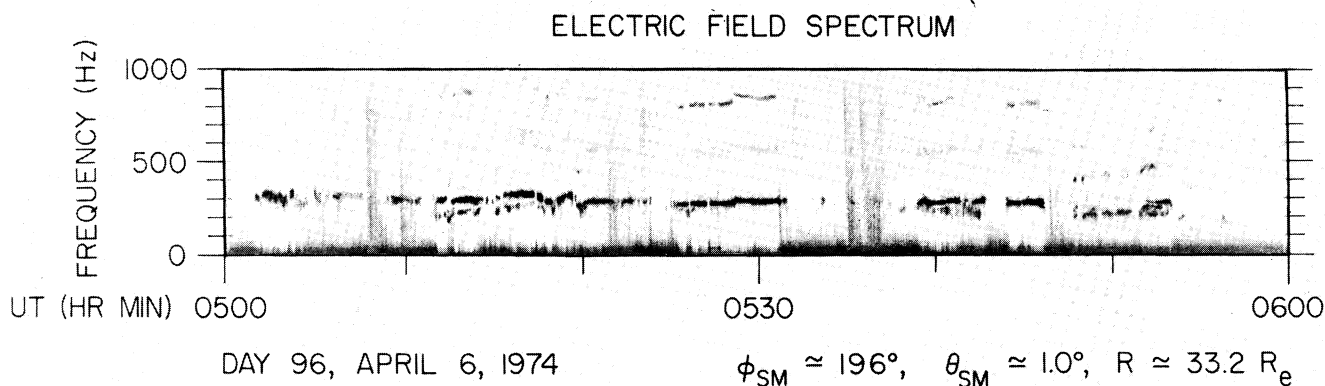


Fig. 14. Frequency-time spectrogram of the electron cyclotron waves shown in Figure 13. The fundamental emission frequency occurs at about 1.21 times the electron gyrofrequency.

after the neutral sheet crossing, a distinct enhancement is evident in the electric field channels from 311 Hz to 1.78 kHz. No comparable enhancement is evident in the corresponding magnetic field channels, indicating that the noise is electrostatic. The broad band electric field strength at the time of peak intensity, at about 0530 UT, is about  $330 \mu\text{V m}^{-1}$ .

A frequency-time spectrogram of the wide band data obtained during this event is shown in Figure 14. This spectrogram shows that the electrostatic noise consists of a strong narrow band emission at a frequency of about 280 Hz and weaker emissions at the second and third harmonics. Although the frequency spectrum of the fundamental is considered reliable, it is possible that the second and third harmonics may be due to nonlinearities in the wide band telemetry system. The existence of emissions above 280 Hz is, however, definitely confirmed by the enhanced electric field intensities in the 562-Hz, 1.0-kHz, and 1.78-kHz electric field channels (see Figure 13). During the interval from 0500 to 0600 UT the electron gyrofrequency varies from about 200 to 250 Hz. Detailed comparisons show that the fundamental frequency of the electrostatic emission occurs at about 1.21 times the electron gyrofrequency. The highest frequency detected, 1.78 kHz, corresponds to the seventh harmonic of the electron gyrofrequency. Because of unfavorable orientations and variations of the magnetic field it has not been possible, in this case or any of the other cases studied, to determine the orientation of the electric field relative to the local magnetic field.

Although electrostatic emissions near the electron gyrofrequency and its harmonics occur very infrequently and are not as intense as the broad band electrostatic noise, these emissions may be of considerable importance because they occur in the same region in which Frank *et al.* [1976] have reported the presence of an extremely hot plasma. For the event shown in Figure 13 the interval from about 0400 to 0630 UT is characterized by a very large increase in both the electron and the proton energies, with average energies greater than 10 keV and electron fluxes  $J(E > 45 \text{ keV}) \approx 5 \times 10^6 \text{ el}(\text{cm}^2 \text{ s sr})^{-1}$ . For further details and an analysis of this event, see Frank *et al.* [1976].

Electrostatic waves of this type, near harmonics of the electron gyrofrequency, have been previously observed in the inner regions of the earth's magnetosphere [Kennel *et al.*, 1970; Fredricks and Scarf, 1973; Shaw and Gurnett, 1975]. Usually, these waves occur near half-integral harmonics of the electron gyrofrequency,  $(n + \frac{1}{2})f_g^-$ . Scarf *et al.* [1974] have also interpreted observations of electrostatic waves detected by Imp 7 in

the distant magnetotail as being due to electrostatic waves at  $\frac{3}{2}f_g^-$  and  $\frac{5}{2}f_g^-$ .

## 7. SUMMARY AND CONCLUSION

These observations have shown that three distinctly different types of plasma wave turbulence are detected by Imp 8 in the distant magnetotail. The first and most frequently occurring type of turbulence, called broad band electrostatic noise, consists of a broad band of electrostatic noise in the frequency range from about 10 Hz to a few kHz. This electric field noise is quite intense, with typical broad band electric field strengths of about  $1 \text{ mV m}^{-1}$  and occasional maximum intensities as large as  $5 \text{ mV m}^{-1}$ . The frequency range of this noise is bounded by the local lower hybrid resonance frequency  $f_{LHR}$  and (except for a few weak bursts) the electron gyrofrequency  $f_g^-$ . The electric field of this noise is oriented perpendicular (within  $\pm 20^\circ$ ) to the local magnetic field, and the wave magnetic field is too small to be detected. Comparisons with the magnetic field and plasma data show that the noise occurs in regions with large magnetic field gradients near the outer boundary of the plasma sheet and is closely associated with large plasma flow velocities, both earthward and tailward, which occur in these regions. In a few cases this noise has also been observed with particularly large intensities directly in the region where the magnetic merging and charged particle acceleration are taking place. Intensity variations of this noise often appear to be closely associated with intense bursts of auroral kilometric radiation generated in the auroral regions near the earth. The second and less frequently occurring type of plasma wave turbulence detected in the distant magnetotail consists of intense ( $100 \text{ m}\gamma$ ) bursts of low-frequency (10–300 Hz) magnetic noise. These magnetic noise bursts, which must be propagating in the whistler mode, occur in regions with large magnetic field gradients near the outer boundaries of the plasma sheet and in the same general region in which the most intense broad band electrostatic noise is observed. The third and least frequently occurring type of plasma wave turbulence detected in the magnetotail consists of electrostatic waves near harmonics of the electron gyrofrequency. Electron cyclotron harmonic waves of this type have only been detected a few times in all of the available Imp 8 data. These waves are relatively weak, seldom exceeding intensities of about  $300 \mu\text{V m}^{-1}$ . Although these waves occur relatively infrequently and are very weak, they may be of considerable importance, since they have been observed in regions where the plasma is being heated to very high temperatures. In contrast to the broad band electrostatic

noise and the whistler mode magnetic noise bursts, the cyclotron harmonic emissions are observed very close to the neutral sheet, i.e., within the high-density region of the plasma sheet.

In considering the plasma wave modes which could be responsible for these different types of noise it is reasonably certain that the magnetic noise bursts consist of whistler mode waves, and the electron cyclotron harmonic emissions consist of  $(n + \frac{1}{2})f_g^-$  electrostatic waves of the type studied by *Fredricks* [1971], *Young et al.* [1973], *Ashour-Abdalla and Kennel* [1976], and others. The exact identification of the plasma wave mode associated with the broad band electrostatic noise is more uncertain. As discussed earlier, this noise has certain spectral characteristics similar to auroral hiss and to the electrostatic noise detected throughout the magnetosheath. The similarity to auroral hiss suggests that this noise consists of short-wavelength quasi-electrostatic whistler mode waves propagating with wave normal directions near the resonance cone. Since hot plasma effects must almost certainly be involved in the generation of this noise, it seems more likely that this electrostatic turbulence consists of ion sound waves or electrostatic ion cyclotron waves of the type discussed by *Kindel and Kennel* [1971] and *Syrovatkii* [1972], which couple with, or are closely associated with, the whistler mode. Coupling effects of this type have been considered by *Sizonenko and Stepanov* [1967] and *Maggs* [1976]. The observed electric field direction of the broad band electrostatic noise, perpendicular to the magnetic field, would appear to favor the identification of this noise with the electrostatic ion cyclotron (Bernstein) modes.

Because substantial field-aligned currents are thought to occur near the outer boundary of the plasma sheet [*Aubry et al.*, 1972; *Fairfield*, 1973] where the broad band electrostatic noise and the whistler mode magnetic noise bursts are observed, it seems most likely that these waves are produced by a current-driven plasma instability. Other instability mechanisms must also be considered, since the exact feature of the charged particle distribution function responsible for the instability remains unknown. The fact that the broad band electrostatic noise is usually detected in regions with large proton streaming velocities suggests that the instability may be driven by some characteristic feature of the proton stream rather than by a current produced by the differential motion with respect to the electrons. If, for example, the streaming protons interact with another more slowly moving ion distribution, such as from the ionosphere, or if multiple peaks occurred in the proton distribution function, then strong two-stream instabilities would be expected. Inspection of the proton velocity distribution function, such as appears in Figure 7 of *Frank et al.* [1976], does not show any evidence of double-peaked distributions. However, these distribution functions require a relatively long time, seconds, to accumulate compared to the short time scales of  $<1$  s evident in the plasma wave spectrums, and it is possible that two-stream interactions of this type could occur within the proton stream, particularly in the highly turbulent region near the fireball. Further detailed studies are needed to clearly identify the instability mechanism involved in the generation of this noise.

When the possible role of this plasma wave turbulence is considered, many questions remain to be investigated. The issue of particular importance is whether the electric field turbulence is sufficiently intense to account for the anomalous resistivity often invoked to explain the existence of merging in an essentially collisionless plasma. We do not attempt to an-

swer this question of theoretical interpretation. However, the measurements in this paper together with the associated plasma and magnetic field measurements of *Frank et al.* [1976] provide the essential experimental parameters (electric and magnetic field frequency spectrums, flow velocities, and particle distribution functions) needed to proceed with a theoretical investigation of the role of anomalous resistivity in the merging region. These measurements also provide evidence that plasma wave turbulence in the distant magnetotail is often closely associated with enhanced auroral activity near the earth (in particular, the auroral kilometric radiation). Whether this relationship can be interpreted as evidence of a plasma wave instability acting to trigger the merging process by increasing the anomalous resistivity, as has been suggested by *Piddington* [1967], *Syrovatkii* [1972], and others, cannot be decided on the basis of these data. The essential interpretational difficulty is that with measurements from a single satellite it is not possible to distinguish spatial variations from temporal variations. Hopefully, measurements from dual spacecraft such as ISEE-A and ISEE-B will help resolve this question.

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