

ISEE Observations of the Plasma Sheet Boundary, Plasma Sheet, and Neutral Sheet

2. Waves

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The companion paper describes the dc electric and magnetic fields, $\mathbf{E} \times \mathbf{B}$ velocities, plasma flow, composition and ground magnetic activity for two periods in the magnetotail near $20 R_E$. The relationship of the plasma waves to the dc field characteristics is described herein. In addition, for two subintervals which had strong ground magnetic activity, we report comparisons of plasma waves in the magnetotail to characteristics of the dc fields and fluid parameters such as the plasma flow, β , density, temperature, and f_{pe}/f_{ce} . Upper hybrid waves at multiples of the electron cyclotron frequency near and above the electron plasma frequency were observed for the first time in this region of the magnetosphere and occurred in regions of low β and temperature and high density. This contrasts with electrostatic electron cyclotron waves which occurred in high-temperature, high-density regions, as previously reported by Gurnett et al. (1976), and were suppressed when $\beta \leq 1$. Both types of waves were associated with small dc electric fields, nonturbulent dc electric and magnetic fields, and plasma flows of ≤ 100 km/s. Broadband electrostatic noise (BEN) and magnetic noise bursts were observed in regions where the dc electric fields and the plasma flows were large, and the dc electric and magnetic fields were turbulent. The dependence of the amplitude and frequencies of BEN on the magnitude of the magnetic field, plasma flow, density, and β was very complex. Enhancements at the upper hybrid frequency and the electron cyclotron frequency were common. BEN was usually suppressed near the neutral sheet but the amplitude reduction varied. The fact that the magnetic noise was most intense during tailward flow and often was not suppressed near the neutral sheet suggests that it may provide the dissipation necessary for reconnection to occur.

1. INTRODUCTION

Knowledge of the plasma waves in the earth's magnetotail is crucial for understanding the physical processes which occur there. Most theories of reconnection, for example, require some kind of dissipation in the neutral line region, and in the collisionless plasma sheet, this dissipation must be provided by waves.

Electrostatic and electromagnetic waves in the distant plasma sheet were first described by *Scarf et al.* [1974], who observed electrostatic noise in the plasma sheet boundary region and electromagnetic noise within the plasma sheet. In a very detailed study of plasma waves in the magnetotail, *Gurnett et al.* [1976] found (1) intense broadband electrostatic noise (BEN), usually extending from the lower hybrid frequency to the electron cyclotron frequency and associated with the boundary and fast

plasma flows, (2) electrostatic electron cyclotron waves which were uncommon and occurred in regions of high temperature and density close to the neutral sheet, and (3) magnetic noise bursts in generally the same regions as, although less common than, BEN. *Anderson* [1984] showed that although waves were enhanced close to the neutral sheet, most were suppressed right at the neutral sheet. *Parks et al.* [1984] presented detailed observations of many types of data at the boundary and found that BEN occurred in regions which had unstable electron distribution functions, as well as field-aligned currents and flowing ions. Theoretical studies of these waves have been made by *Huba et al.* [1978], who proposed that the lower hybrid drift instability could account for both broadband electrostatic noise and the magnetic noise. *Grabbe and Eastman* [1984] suggested that ion beam instabilities produced the broadband electrostatic noise.

Cattell et al. [this issue] (hereafter referred to as paper 1) described the dc electric and magnetic fields, $\mathbf{E} \times \mathbf{B}$ velocities, plasma flow, total energy density, high time resolution 2-keV particles, composition, and ground and interplanetary magnetic fields for two different periods in the tail near $\sim 20 R_E$. These events included both turbulent and quiet crossings of the neutral sheet and plasma sheet as defined by the dc electric field experiment [see *Cattell and Mozer*, 1982] and two well-defined substorm onsets during which the observations supported the hypothesis that a neutral line formed earthward of the satellite.

In this paper, we will discuss the relationship of the

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Paper number 5A8888.
0148-0227/86/005A-8888\$05.00

plasma waves to the characteristics of the dc electric and magnetic fields (as well as plasma flow) for both periods. In addition, we will present higher time resolution data including the ac and dc fields, the earthward-tailward component of the plasma flow, β (the ratio of plasma to magnetic field pressure), f_{pe}/f_{ce} (the ratio of the electron plasma frequency to the electron gyrofrequency), and the density for two shorter intervals. These intervals were chosen to include a ground substorm onset event with tailward flow at ISEE and an event with large earthward flows and ground activity but no clear substorm signature, in part in order to determine whether there were any systematic differences between waves observed in association with signatures of reconnection and those associated with other large flows. We address the association of plasma waves in the magnetotail to fluid parameters rather than to features in either the electron or ion distribution functions.

A brief description of the data is given in section 2. The large-scale features of the waves and dc fields are described in section 3, and the higher time resolution data are given in section 4. Discussion and conclusions are presented in section 5.

2. INSTRUMENTATION

Data from the dc electric field experiment [Mozer *et al.*, 1978], the magnetometers [Russell, 1978], and the fast plasma experiment [Bame *et al.*, 1978] were described in paper 1. In addition to the parameters presented there, plots of the negative of the spacecraft potential V_{2s} (which is indicative of the plasma density) will be shown.

The ac electric and magnetic fields were measured by the University of Iowa plasma wave instruments [Gurnett *et al.*, 1978]. The plots herein present the data from the 20-channel electric field analyzer (5.6 Hz–311 kHz) and the 14-channel magnetic field analyzer (5.6 to 10 kHz) on ISEE 1. The wideband data were also examined for selected time periods.

3. OVERVIEW OF THE WAVES

In this section, summaries of the ac and dc electric field and dc magnetic field for the two events of interest are described in order to show the relationship between large-scale characteristics of the dc fields and large-scale features in the waves. A detailed description of the dc fields and plasma measurements, as well as ground magnetic activity, can be found in paper 1.

The field data for the March 30, 1980, event are presented in Figure 1. The bottom panels show 1-min averages of the total magnetic field magnitude, the three components of the magnetic field in geocentric solar ecliptic coordinates, and the dawn-dusk component of the electric field. The top panel contains the ac electric field data from 5.62 to 311 Hz. The location of the satellite in geocentric magnetospheric coordinates (x , y , and $z - z_{NS}$, where z_{NS} is the nominal location of the neutral sheet) and the Ae index [Kamei *et al.*, 1983] are also given.

Several zero crossings of B_x , and minima in B_T , indicative of neutral sheet crossings, can be seen. These data have examples of both quiet and turbulent neutral sheet

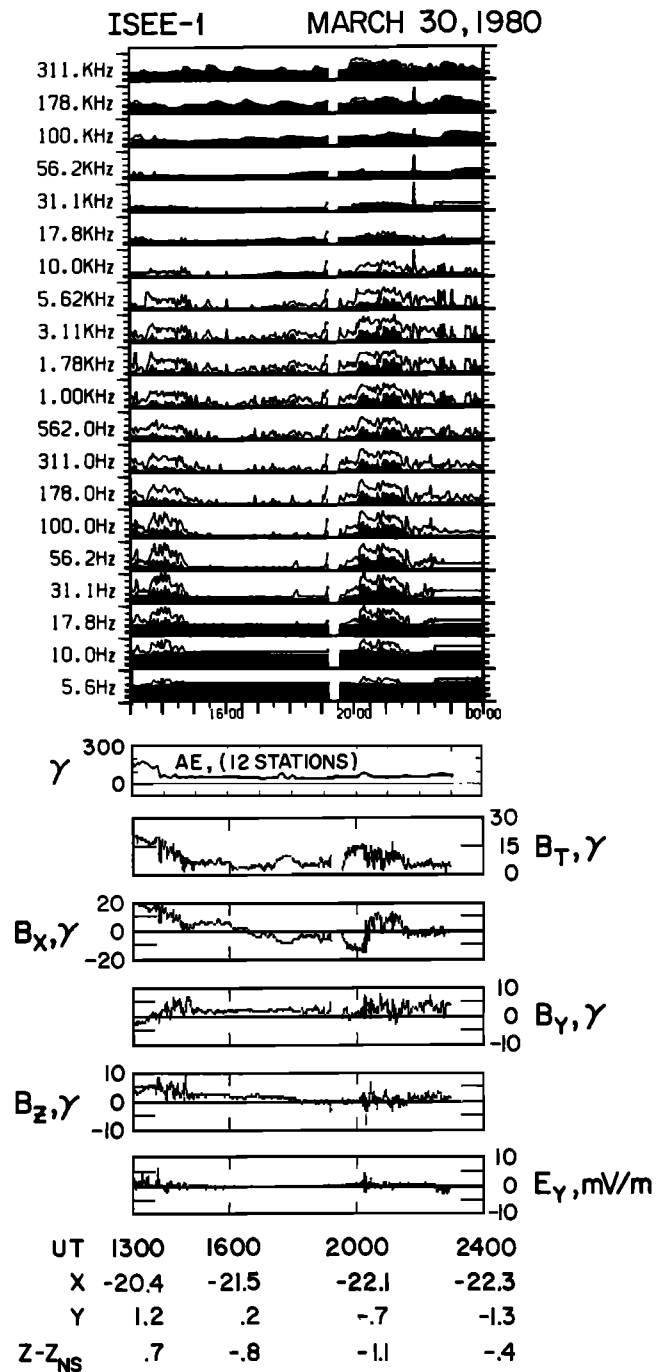


Fig. 1. The 1-min averaged total magnetic field, B_T , the three components of B in GSE, B_x , B_y , and B_z , the 1-min averaged dawn-dusk electric field, and the electric field at frequencies from 5.6 Hz to 311 kHz for March 30, 1980, 1300–2200.

crossings, which were defined as having σ_E , the standard deviation in the 3-s spin period fit of the electric field, <0.7 mV/m (quiet) or ≥ 0.7 mV/m (turbulent) by Cattell and Mozer [1982]. (The characteristics of the dc electric and magnetic fields from 1500 to 2200 were described in that paper.) The regions with large dc electric fields and large fluctuations in the dc electric and magnetic fields (~ 1300 – 1500 , an encounter with the plasma sheet boundary, and ~ 2000 – 2200 , which had “turbulent” neutral sheet crossings) also contain broadband electrostatic noise

[Gurnett *et al.*, 1976]. These boundary regions also had large spiky fields observed in the raw (8 samples/s) dc electric field data of the type described by Cattell *et al.* [1982]. The most intense waves occurred during the fastest plasma flows (~1345–1430 and ~2015–2140, see Figures 2 and 3 of paper 1 for flows). Magnetic noise bursts were also observed in these regions. The “quiet” crossing of the plasma sheet and neutral sheet (~1500–1900) had very little wave activity, especially at frequencies below ~300 Hz. A burst of BEN began just before the ISEE 1 data dropout at ~1911. Examination of the ISEE 2 data during the ISEE 1 dropout shows the waves continued until ~1927 (although they were weaker from ~1912 to ~1916, when there are indications that the satellite was in the lobe). As described in paper 1, the period beginning at ~1910 may have been associated with the formation of a neutral line earthward of the satellite.

In addition to BEN, type III bursts (in 56 or 100 kHz to 311 kHz bands throughout the event) and auroral kilometric radiation (AKR) (in the 100–311 kHz bands from ~2000 to ~2300 UT and possibly also at 1300–1330) can be identified in Figure 1. The occurrence of AKR can be used as an indicator of auroral activity [Shawhan, 1979].

Figure 2 presents the field data for March 25–26 event in the same format as that of Figure 1. Once again, the signatures of many neutral sheet encounters (zeroes in B_x ; minima in B_T) can be seen. The most obvious characteristic of both the electric and magnetic fields is their variability, and almost all of these crossings can be classified as turbulent crossings. The largest electric fields were associated with the two substorms (onset times ~0225 and 0501) and with the period of large A_e from ~2100 to 2300. On the average, B_z was northward, suggesting that the satellite was usually earthward of the neutral line, except for a period during each of the substorms. Broadband electrostatic noise was observed essentially throughout the time period. Note that BEN is actually impulsive, but the individual bursts can not be distinguished on this compressed time scale. This will be apparent in the higher time resolution data presented in section 4. There were enhancements (particularly in the low frequencies) during the substorms and from ~2100 to ~2300, i.e., the same periods which had large dc electric fields. The least intense waves occurred from ~1705 to 2030 and ~0330 to 0500 in regions where the dc electric field was small, the dc electric and magnetic fields were quiet, and the plasma flows were generally <50 km/s. Auroral kilometric radiation, type III radio bursts, and bursts of magnetic noise (not shown) to ~311 Hz were also common. For example, from ~2130 to ~2300, both AKR and type III bursts were observed in close association, as discussed by Calvert [1981]. The waves during the periods 2100–2300 and 0200–0400 are described in detail below.

4. DETAILED WAVE DATA

The relationship of the plasma waves to β (the ratio of the plasma pressure to magnetic field pressure), to f_{pe}/f_{ce} (the ratio of the electron plasma frequency to the electron gyrofrequency), to the plasma velocity, to the dc magnetic and electric fields and to the density is shown in greater

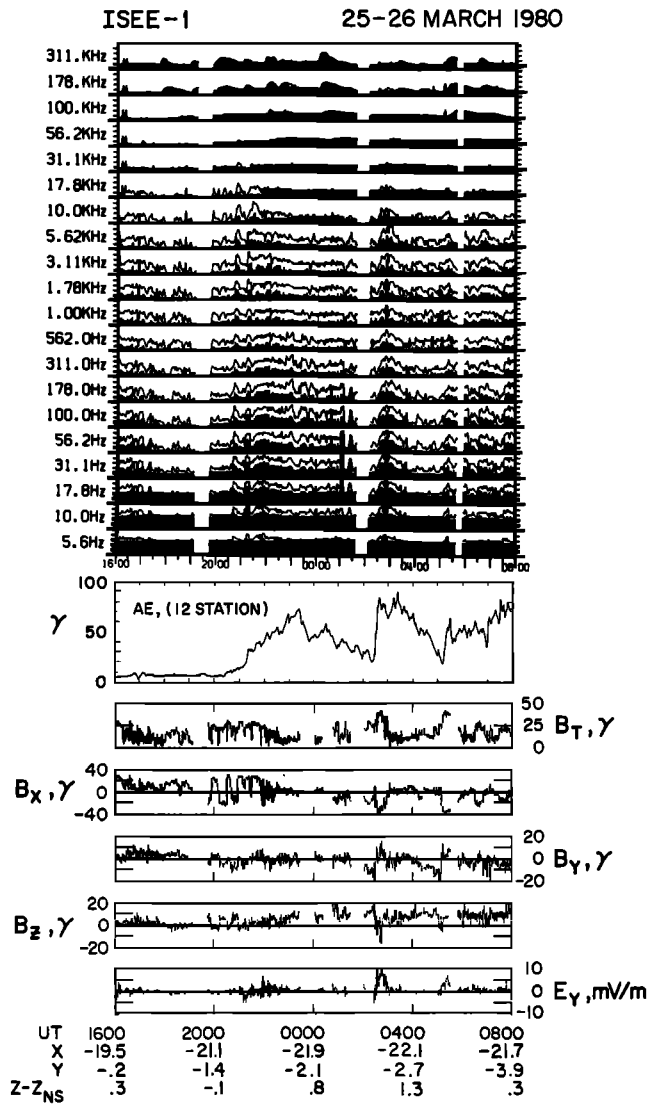


Fig. 2. Same as Figure 1 for March 25, 1600 to March 26, 0900, 1980.

detail for two 2-hour periods in Figures 3 and 4. In both figures, the top two panels contain the 14 magnetic field channels from 5.6 Hz to 10 kHz and the 20 electric field channels from 5.6 Hz to 311 kHz from the University of Iowa plasma wave instruments; the third panel contains a plot of the log of β ; the fourth panel has a plot of f_{pe}/f_{ce} ; the fifth panel contains the x component of the plasma velocity, the next three panels contain the total magnitude and the x and z components of the magnetic field in GSE; and the final two panels contain the dawn-dusk component of the electric field and the negative of the spacecraft potential V_{2s} . V_{2s} provides information on changes in the plasma density [see Mozer *et al.*, 1983]. Increases (decreases) in the V_{2s} correspond to increases (decreases) in the density.

Figure 3 presents the data from 2100 to 2300 UT on March 25. As described in paper 1 (see also panel c), there was tailward flow with northward B_z from ~2112 to ~2118 UT; earthward flow from ~2131 to ~2135, 2145 to 2148, and ~2152 to ~2200; and strong earthward flow (~400–700 km/s) from 2200 to 2300. Although K_p was 4-

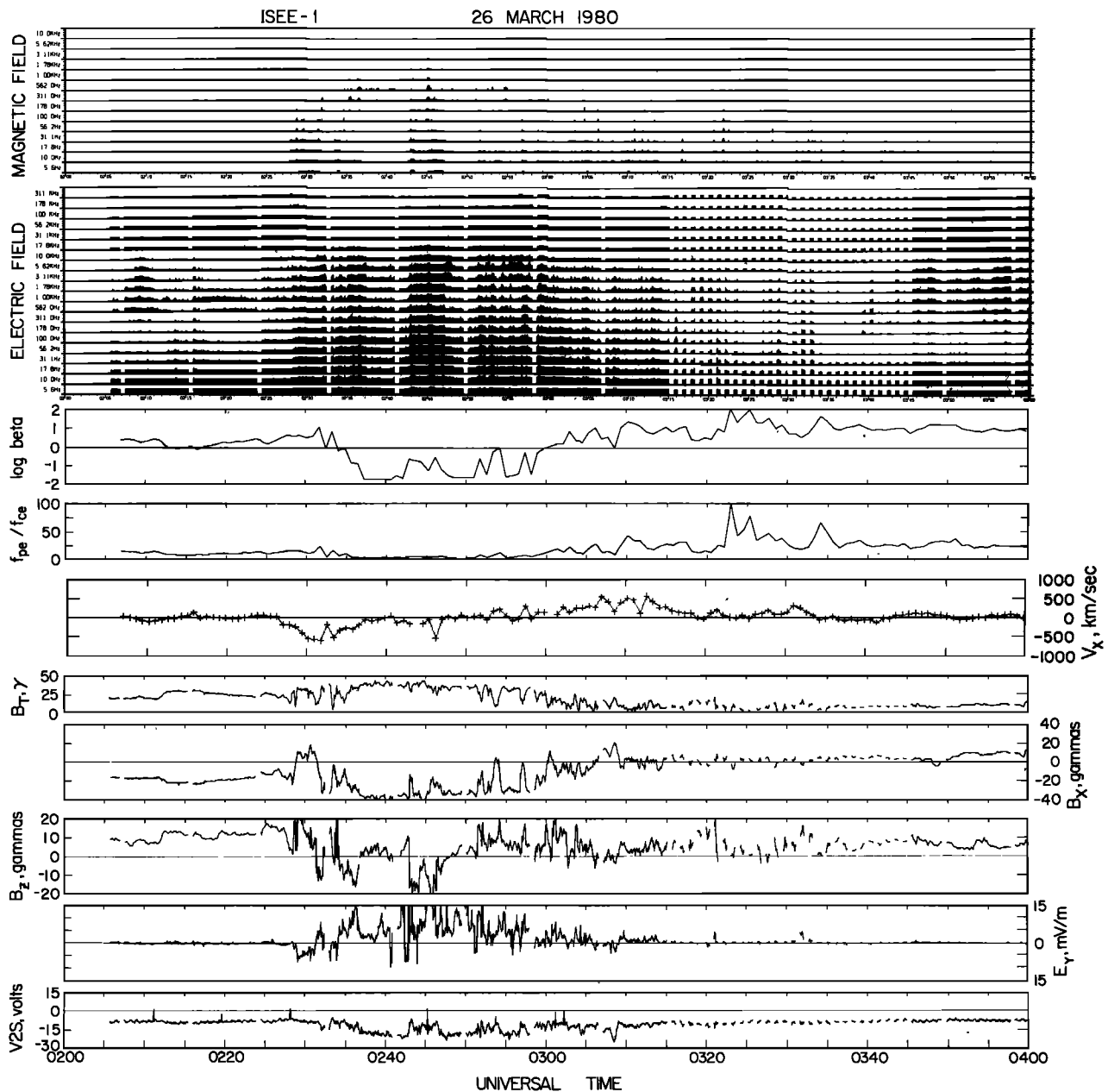


Fig. 4. Same as Figure 3 for March 26, 0200-0400.

~6 kHz. These waves have therefore been identified as upper hybrid waves. The wideband data show that the waves occurred from ~2119 to ~2128 with a lower cutoff near the upper hybrid frequency which varies from 3 to 10 kHz during that time. The waves occur at $(n + 1/2)$ multiples of the cyclotron frequency as described theoretically by Gaffey and LaQuey [1976] in reference to waves in the plasmasphere. Waves of this type were observed only during this time period. Their occurrence in this region of the magnetosphere has not previously been reported. The only difference between the plasma parameters here and during the rest of the events is that the plasma frequency (i.e., density) was larger than during any other period when $\beta < 1$. The region had both a high density and a large magnetic field in comparison to other times. In addition, the proton temperature reached a

minimum for this event. The dc electric field and plasma flow were both small, and the dc electric and magnetic fields were quiet. Line emissions at the upper hybrid frequency were also observed at ~2109-2112, followed by a region of broadband electrostatic noise enhanced at the upper hybrid frequency.

In addition, there were occasional bursts of multiple bands at $(n + 1/2)f_{ce}$ beginning at f_{ce} (rather than at f_{uh}) from ~2100 to ~2111 primarily in regions where $\beta > 1$. This wave mode was previously observed in the magnetotail by Gurnett et al. [1976]. During times when the satellite was in the lobes, a weak narrow line emission near f_{ce} was usually observed. The two most common types of waves observed in the plasma sheet, broadband electrostatic noise and magnetic bursts, will be discussed below with reference to both Figures 3 and 4.

The data plotted in Figure 4 cover 0200–0400 on March 26, 1980. As described in paper 1, signatures of reconnection at ISEE (anticorrelated E_y and B_z , and tailward flow) were observed at this time in association with a ground substorm onset at ~ 0225 . The plasma flow (Figure 4, fifth panel) was tailward from ~ 0227 to 0237 and ~ 0242 to ~ 0247 , and earthward from ~ 0251 to ~ 0315 .

The same types of waves were observed during this event as during the previous one, except that upper hybrid waves at multiples of f_{ce} did not occur. AKR began at ~ 0227.5 in the 178-kHz and 311-kHz channels just prior to the observation of BEN associated with the tailward flow. It was subsequently observed at ~ 0242 and ~ 0246 (178 kHz), and ~ 0250 – 0257 (178–311 kHz).

From ~ 0207 and ~ 0214 , strong wave emissions were observed beginning in the 562-Hz channel (which was approximately equal to the electron cyclotron frequency) and extending up to approximately the plasma frequency. These waves have therefore been identified as electrostatic electron cyclotron waves which have been previously observed in the plasma sheet by Gurnett *et al.* [1976]. As Gurnett *et al.* also described, these waves occurred in a region of high-temperature, high-density plasma. Figure 4 shows that the waves also occur in a region which has the plasma velocity < 100 km/s and small, quiet dc electric fields. The waves were suppressed at ~ 0214 when β dropped to 1 and reappeared (although weaker) at ~ 0216 when β increased above 1. Examination of the broadband data showed that a line emission at $\sim f_{ce}$ occurred throughout the region from 0200 to 0228, with occasional periods of multiple $(n + 1/2)f_{ce}$ harmonics. Multiple harmonics also occurred at ~ 0237 . Electrostatic electron cyclotron waves were observed again from ~ 0345 and ~ 0400 (possibly they began as early as ~ 0339 , but the data gaps due to the operation of the active experiment make positive identification difficult). The plasma density and temperature were also high in this region. The flows and electric field were small, $\beta > 1$, and there were occasional crossings of the neutral sheet. Enhanced emissions at the upper hybrid frequency were observed in the broadband data at ~ 0237 , 0243, and 0247.

Broadband electrostatic noise, the most ubiquitous wave type observed during these events, extends from either the 5.6- or the 10-Hz channel (consistent with the finding of Gurnett *et al.* [1976] that the noise cuts off at the lower hybrid frequency) to well above the electron cyclotron frequency and often to the electron plasma frequency. At times, enhancements at the upper hybrid frequency and/or the electron cyclotron frequency were observed in the broadband data during periods of BEN. BEN occurred when there were gradients in the magnetic field and/or density and/or where there were large plasma flows, any of which could provide free energy to drive the waves. Comparison of properties of BEN to β , f_{pe}/f_{ce} , the magnitude of the magnetic field, and the plasma flow velocity provides constraints on the wave mode or modes. For example, the maximum frequency of the emissions does not depend on the plasma flow velocity, whereas if the high-frequency portion of the spectrum were due to Doppler shifting as suggested by Huba *et al.* [1978], one would expect the maximum frequency to increase with

the plasma flow velocity. The dependence of the intensity of the waves on both β and the magnitude of the magnetic field is extremely complex. The waves tend to be suppressed at both very high β and very low β , especially in the highest and lowest frequency ranges. Often these are regions where the gradients in the magnetic field and density are smaller (e.g., 0320–0400 on March 26). Therefore, in addition to whatever stabilization is provided by finite β effects, there may be less free energy available to drive the waves. The wave intensity is also reduced when the magnetic field is small (i.e., at or near the neutral sheet) (see also Anderson [1984]) regardless of the value of β . If one looks, for example, at all the times when $|\mathbf{B}| \leq 5 \gamma$, one almost always can see a decrease in strength of the waves, but the amount of this decrease varies dramatically. Sometimes it cannot be distinguished from the small-scale modulation which gives BEN its bursty character. The three minima in $|\mathbf{B}|$ on March 25 from ~ 2155 to ~ 2159 , the first and third of which all occurred during earthward flows of ~ 400 km/s, provide an illustration of this phenomenon. At 2155 there was a decrease in the wave intensity coincident with the minimum in $|\mathbf{B}|$. However, only above the 562-Hz channel was this decrease larger than several not associated with low $|\mathbf{B}|$ occurring between 2155 and the next minimum in $|\mathbf{B}|$ at 2157. At ~ 2157 , in a region where the plasma flow was much slower, only the waves above 1 kHz were suppressed. In contrast, waves throughout the BEN frequency range were reduced almost to background levels in association with the minimum at ~ 2158.5 . Another example can be seen from ~ 2211 to ~ 2213 and at ~ 2214 . In this case, there was a broad dip in the wave power, particularly at high frequencies, associated with the broad minimum in $|\mathbf{B}|$ from 2211 to 2213. However, there were small-scale enhancements in the waves within this region associated with small-scale changes in $|\mathbf{B}|$. The waves at all frequencies were more suppressed at ~ 2214 in a region where the flow was still ~ 700 km/s. In general, the small-scale modulations in BEN are well correlated with small-scale variations in $|\mathbf{B}|$ and the density (as shown by the spacecraft potential, V_{2s}) in both figures.

The final waves to be discussed are the magnetic bursts, which have been identified as whistler mode waves [Gurnett *et al.*, 1976]. These waves are usually confined to well below the electron cyclotron frequency but occasionally are observed up to that frequency. The broadband data show periods when line emissions at f_{ce} (near neutral sheet crossings from 2109 to 2119) or $f_{ce}/2$ (0237 and ~ 0245) occurred.

The magnetic bursts occur in generally the same region as broadband electrostatic noise but do not exhibit the same dependence on β or $|\mathbf{B}|$. For example, there were usually no dips in the magnetic noise when there were dips in the BEN wave intensities associated with minima in $|\mathbf{B}|$. In fact, enhancements were sometimes seen at the neutral sheet crossings (e.g., ~ 0228 on March 26). When BEN was suppressed due to low β , for example, from ~ 0237 to 0243 on March 26, the magnetic noise continued in the 562-Hz channel. Note that the example in Figure 2 of Scarf *et al.* [1974] also showed that the magnetic noise was not suppressed at the neutral sheet

and that *Coroniti et al.* [1977] also discussed observations of enhanced magnetic noise in regions near the neutral sheet. There is some indication that the magnetic noise bursts are more intense during tailward flow (i.e., the regions around ~ 2115 , ~ 0230 , and ~ 0245).

5. DISCUSSION AND CONCLUSIONS

The observations of plasma waves during the two subintervals which were both active magnetically have shown the complexity of broadband electrostatic noise and its dependence on plasma flows, β , f_{pe}/f_{ce} , and gradients in the magnetic field and density and have, therefore, provided constraints on which modes could produce the waves. We have shown additional examples of the behavior of plasma waves near the neutral sheet previously described by *Anderson* [1984]. In particular, BEN is often strong near neutral sheet crossings but suppressed right where $B_x = 0$ and B_T is at a minimum. The amount of suppression is quite variable and often not distinguishable from the general burstiness of the wave noise. The magnetic noise does not appear to be related to BEN and has a very different dependence on $|B|$ and β (showing that they are due to different wave modes, as stated by *Gurnett et al.* [1976]). These facts about BEN and magnetic noise indicate that it is unlikely that both may be completely explained by the lower hybrid drift instability, as suggested by *Huba et al.* [1978]. BEN may be the superposition of several wave modes, as suggested by the fact that it often contained enhancements at either or both the electron cyclotron frequency and the upper hybrid frequency. Since the most intense broadband electrostatic noise often occurs in the same regions which contain large-amplitude spiky electric fields in the raw dc data, it is also possible that BEN is due to an ensemble of nonlinear waves, as described by *Lotko* [1983]. Since the magnetic noise was often not suppressed near the neutral sheet (unlike BEN) and was, in fact, observed during neutral sheet crossings occurring during tailward flow interpreted as being due to a near-earth neutral line (paper 1), it may be important in providing dissipation for reconnection. This is consistent with the suggestion of *Coroniti* [1980] that whistlers in the neutral line region would scatter electrons and thus destabilize the tearing mode. Both broadband electrostatic noise and the magnetic noise bursts occurred in regions where the dc electric fields were large and both the dc electric and magnetic fields were turbulent. The most intense BEN was associated with the most turbulent dc fields and therefore also the largest plasma flows.

We reported the first observations in the magnetotail of upper hybrid waves occurring at multiples of the electron cyclotron frequency. In contrast to electron cyclotron waves, which are suppressed in regions of low β and were associated with high densities and temperatures, the upper hybrid waves occurred in a region where $\beta < 1$ and the density was, nonetheless, relatively large and the ion temperature was low. Both the upper hybrid waves and the electrostatic electron cyclotron waves were associated with regions where the dc electric field was small (usually $\leq 1/2$ mV/m) and quiet, and the plasma flows were ≤ 100 km/s.

Comparison of the wave data with the ion composition data in paper 1 suggests that the observed waves are not dependent on the ion composition. Since the ion frequencies are at the lower end of the spectrum, this is not an unexpected result. A more detailed study of the very low frequency waves is necessary to see the effect of ion composition.

Acknowledgments. The authors thank D. Gurnett for providing the plasma wave data and C. T. Russell for providing the ISEE 1 and 2 magnetometer data. One of the authors (C.A.C.) thanks Sharon Primbsch and Winston Teitler for programming and Carolyn Overhoff for preparation of the manuscript. Ground magnetograms were obtained from the World Data Center. The ISEE Attitude-Orbit Listings of C. T. Russell have been provided by the National Space Science Data Center. This research has been carried out under NASA grants NAG5-375 and NAS5-25770 at University of California, Berkeley, NAS5-25773 at Lockheed Palo Alto Research Laboratories, NAS5-28702 at Los Alamos National Laboratory, and NAS5-28701 at the University of Iowa.

The Editor thanks D. H. Fairfield and another referee for their assistance in evaluating this paper.

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(Received September 30, 1985;
revised December 9, 1985;
accepted December 10, 1985.)