

# ISEE 1 and Geotail observations of low-frequency waves at the magnetopause

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**Abstract.** Observations of waves at frequencies below  $\sim 200$  Hz obtained near the magnetopause are presented. For one case identified in the ISEE 1 data as a period when steady state reconnection was occurring, there were waves below the lower hybrid frequency with amplitudes up to  $\sim 7$  mV/m. Intense low-frequency waves with amplitudes up to  $\sim 20$  mV/m at the subsolar magnetopause have also been observed by the Geotail electric field instrument. In some cases, large spiky fields were embedded in the waves. The waves observed by ISEE 1 and Geotail were large enough to provide the dissipation required for reconnection to occur.

## 1. Introduction

Many models of steady state reconnection have been developed [Petscheck, 1964; Sonnerup, 1970; Vasyliunas, 1975; Sonnerup *et al.*, 1990, and references therein]. For these models to be valid in the collisionless plasma of the Earth's magnetopause, most require that some type of process operate near the neutral line to provide anomalous dissipation. Theoretical studies have suggested various possibilities including waves such as lower hybrid drift waves [Huba *et al.*, 1977, 1978; Gary and Eastman, 1979] and ion acoustic waves or non-adiabatic motion of the particles. Early in situ magnetic field evidence for reconnection was provided by Sonnerup and Cahill [1968] and Aubry *et al.* [1970]. More recently, in situ observations utilizing other types of data and providing support for the occurrence of quasi-steady reconnection at the magnetopause were presented by Mozer *et al.* [1979], who examined the tangential component of the electric field, and by Sonnerup *et al.* [1981], who studied tangential momentum balance. Both studies utilized data from the ISEE spacecraft. Further refinements were made using the higher time resolution three-dimensional plasma data from the AMPTE/IRM satellite [Paschmann *et al.*, 1986; Sonnerup *et al.*, 1987].

Various studies of waves at the magnetopause [Gurnett *et al.*, 1979; Anderson *et al.*, 1982] suggested that

the wave power was not sufficient to provide the required dissipation. Cattell and Mozer [1988] showed a case which suggested that the wave amplitudes were, at times, large enough. A detailed statistical study of the AMPTE/IRM wave data was performed by LaBelle and Treumann [1988], who concluded that the waves were too weak to have important dynamic effects. However, Gary and Sgro [1990] pointed out an error in their calculation and suggested the dissipation could be higher. In addition, Gary and Sgro [1990] discussed the possible inapplicability of the quasi-linear expression for cross field transport but did not explicitly discuss the effects on anomalous resistance in a field-reversal geometry. Treumann *et al.* [1991] showed the waves were large enough to explain the boundary layer during non-reconnection times.

In this paper, we present electric field data from the ISEE 1 and Geotail spacecraft to address the question of whether the observed waves are large enough to provide the anomalous resistance necessary for reconnection. In section 2, the data set and experimental approach are presented; examples of magnetopause wave observations are discussed in section 3; and calculations of resistance and conclusions are given in section 4.

## 2. Data and Experimental Approach

Data from the ISEE 1 satellite which will be shown herein include the following: (1) electric field measurements from the University of California at Berkeley spherical double probe [Mozer *et al.*, 1978]; (2) magnetic field measurements from the University of California at Los Angeles magnetometers [Russell, 1978]; and (3) plasma moments from the Los Alamos National Laboratory/Max-Planck-Institut plasma detectors [Bame *et al.*, 1978]. Three different types of measurements from the electric field instrument are utilized. Waves at frequencies from  $\sim 2$  to 128 Hz were obtained in the burst mode which took either a 0.5- or a 0.25-s snapshot of the field every 128 s. The potential of the

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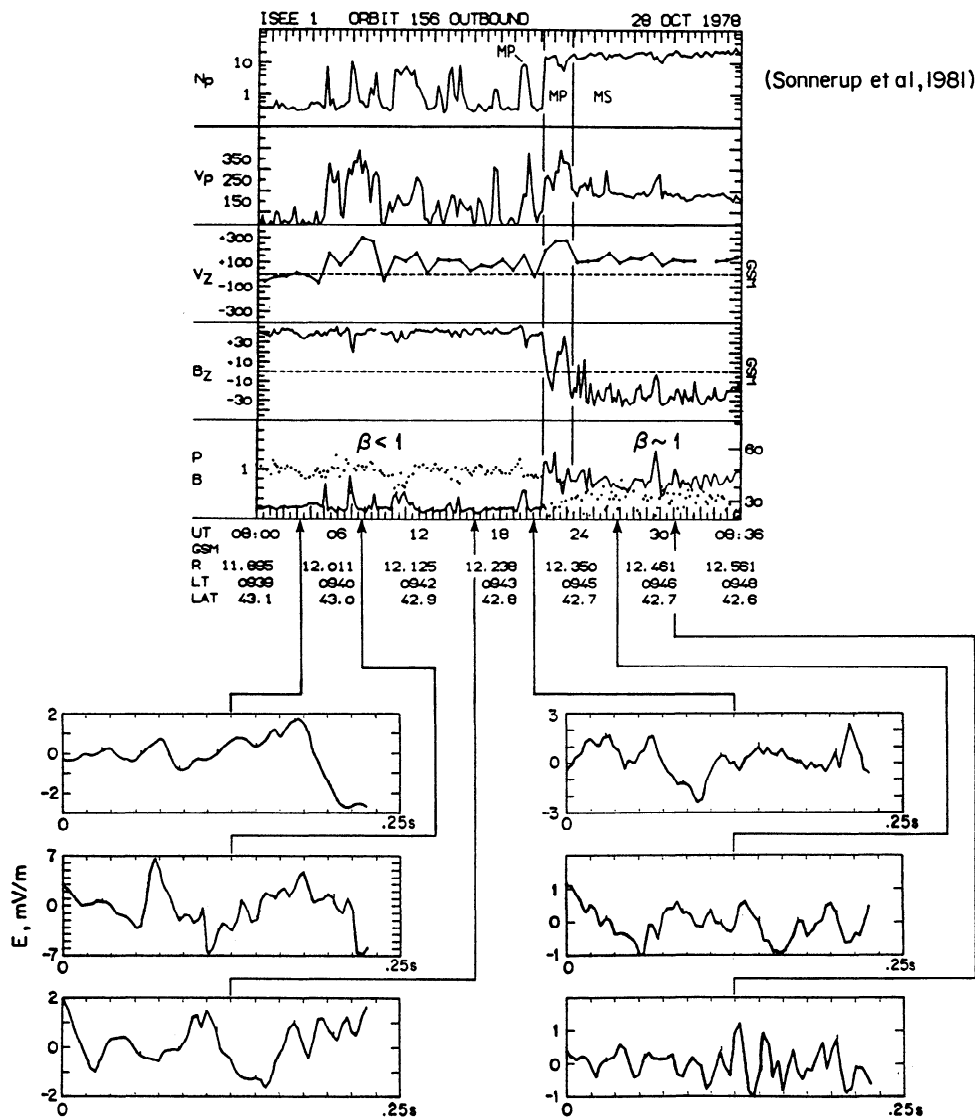
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spacecraft relative to the probes provides an estimate of the thermal plasma density [Mozer *et al.*, 1983; Pedersen, 1994]. In addition, assuming that  $\mathbf{E} \cdot \mathbf{B} = 0$ , the  $\mathbf{E} \times \mathbf{B}/B^2$  convection velocity could be calculated with spin period (3 s) resolution.

The double-probe instrument on the Geotail satellite [Tsuruda *et al.*, 1994] also provides measurements of the dc electric field, the spacecraft potential and waves up to  $\sim 32$  Hz. Higher-frequency measurements were obtained by the plasma wave detector [Matsumoto *et al.*, 1994]. The magnetic field measurements [Kokubun *et al.*, 1994] shown herein are spin period averages.

The approach taken in this study was to identify candidate reconnection events utilizing: (1) the study of Sonnerup *et al.* [1981] and (2) the University of Cali-

fornia, Los Angeles list of magnetopause crossings (C. T. Russell and G. Le, private communication, 1993), for the ISEE studies and (3) subsolar magnetopause crossings in the Geotail data. In this paper, we present results from the (1) and (3); statistical results from (2) will be described in a forthcoming paper. For the selected events, the electric field waveforms were examined to determine whether the waves appeared to be linear or nonlinear and whether there were embedded large spiky fields. Spectra were next made and compared to various plasma wave frequencies, in particular, the lower hybrid frequency. For the cases herein (which are in the regime where  $f_{ci} < f_{lh} < f_{pi}$ ,  $f_{ce} < f_{pe}$ ), the lower hybrid frequency is given by  $f_{lh} \approx (f_{ce}f_{ci})^{1/2}$ . After wave power and frequency levels were determined,



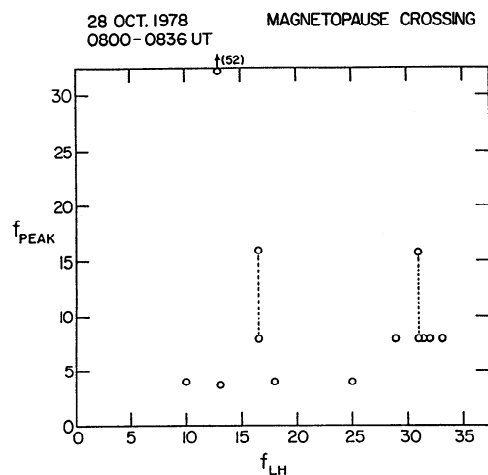
**Figure 1.** Plasma and field data from the ISEE 1 satellite on October 28, 1978. The top panels are from Figure 6 of Sonnerup *et al.* [1981] and plot the ion density, ion flow speed, Z component of the magnetic field and the plasma (solid) and magnetic field (dotted) pressures. Six 0.25-s snapshots of the electric field, obtained at the indicated times, are in the bottom half of the figure.

the resistivity which the waves could provide was calculated based on *Gary* [1980] and *Coroniti* [1985]. Note that these are both quasi-linear calculations.

### 3. Examples of Observations

ISEE 1 passed from the magnetosphere into the magnetosheath at  $\sim 0820$  UT on October 28, 1978. This magnetopause crossing was analyzed in detail by *Sonnerup et al.* [1981], who showed that the plasma and magnetic field observations were consistent with the occurrence of steady reconnection. The top panels in Figure 1 are from Figure 6 of *Sonnerup et al.* [1981] and plot the ion density, the magnitude of the ion velocity, the  $Z$  component (northward) of the ion velocity, the  $Z$  component of the magnetic field, and the plasma (solid line) and magnetic field (dots) pressures. Jetting of plasma can be seen in association with the magnetopause crossing marked by the two vertical lines. This plasma flow was consistent with the existence of a normal component of the magnetic field (for further details, see *Sonnerup et al.* [1981]). Six 0.25-s snapshots of the electric field are plotted in the lower half of Figure 1 corresponding to the times indicated by the arrows. The 0.25-s duration of the snapshot corresponds to about one-tenth of the spin period so no spin modulation due to the motion of the probes in the background dc electric field can be seen. Note that the amplitude scale varies from snapshot to snapshot. The observed amplitudes vary from  $\sim 2$  to  $\sim 14$  mV/m peak to peak. This latter value is the instrumental saturation level. The largest amplitude waves usually occurred in the lower  $\beta$  regions (i.e., low plasma pressure, high magnetic field pressure). There were no large spiky fields during any of the samples in the time period which was examined (0800–0940 UT).

The frequencies at the peak power in the Fourier transform of each sample are plotted versus the lower hybrid frequency (assuming 100%  $H^+$ ) in Figure 2.



**Figure 2.** The frequency at which the peak power occurred for each electric field snapshot during the period covered by Figure 1 is plotted versus the lower hybrid frequency (assuming 100%  $H^+$ ).

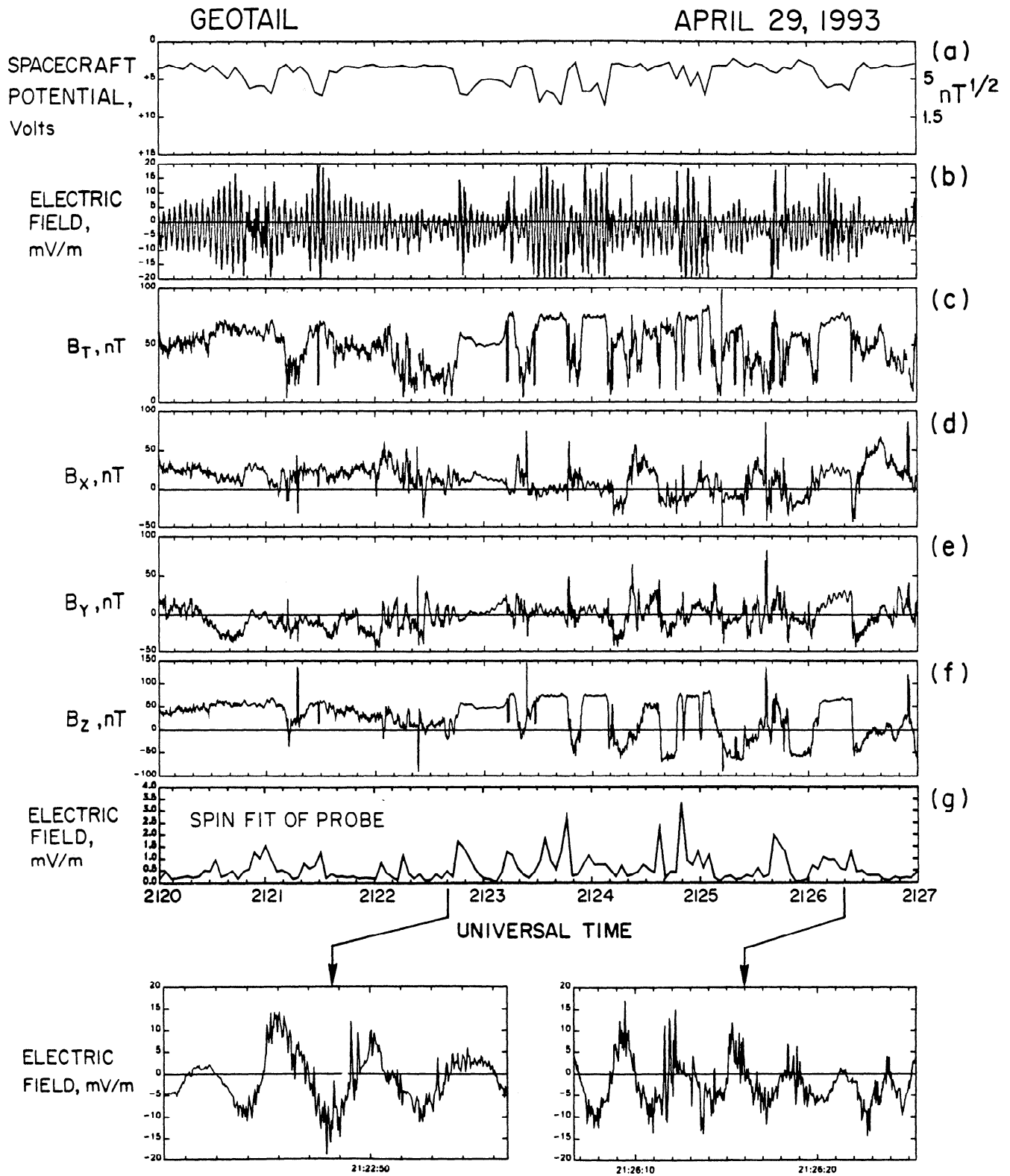
When there were two peaks with comparable power, they were both plotted connected by a dotted line. It can be seen that the peak frequencies were usually  $\lesssim 0.5 f_{LH}$  which is consistent with the theory of lower hybrid drift waves (see, for example, *Huba et al.* [1977, 1978]).

During a period near the end of April 1993, Geotail skimmed the magnetopause making multiple crossings of that boundary. Many subsolar crossings occurred on April 29, 1993, and a set of these is shown in Figure 3. The spacecraft potential (panel a) is proportional to  $nT^{1/2}$ ; increases in the potential correspond to decreases in the plasma density. An approximate calibration is indicated [*Mozer et al.*, 1994]. The raw electric field is plotted in Figure 3b; a sine wave at the spin period is clearly visible due to the modulation of the measured field along the booms as they rotate in the background quasi-static field. The magnitude and three components of the magnetic field in GSE are given in Figures 3c–3f. Multiple crossings of the magnetopause can be seen in the northward ( $B_z$ ) component. The standard deviation of the least squares fit of the electric field (shown in Figure 3g) provides an indication of the periods when turbulence was the largest. Expanded views of the raw electric field at two times are shown below. Higher-frequency quasi-sinusoidal waves can be seen superimposed on the 3-s period variation due to the booms spinning in the background dc electric field. These wave amplitudes occasionally reached 20 mV/m peak to peak; amplitudes of 5 to 10 mV/m were more common. Fourier transforms of the data show peaks comparable to, but below the lower hybrid frequency, similar to the ISEE 1 data. In addition, the Geotail data provide examples of large spiky electric fields embedded in the low-frequency waves. The spikes may be due to the nonlinear evolution of the waves. This is the first time such spiky fields have been observed at the magnetopause, although similar large amplitude spikes were associated with lower hybrid waves in the magnetotail [*Cattell et al.*, 1994; *Cattell and Mozer*, 1987]. The dependence of the wave amplitudes on plasma density is indicated in Figures 4a and 4b. During both periods, there were density depletions visible in the spacecraft potential (top panel). It can be seen that the most intense waves occurred at the density gradients as well as in the region of lowest density. The association of large field strengths with low densities provides an indication that there is nonlinear evolution of the waves, which lends credence to the idea that the spiky fields are due to the nonlinear evolution of the waves. This association of intense waves with gradients is in agreement with Geotail observations in the tail [*Okada et al.*, 1994; *Cattell et al.*, 1994].

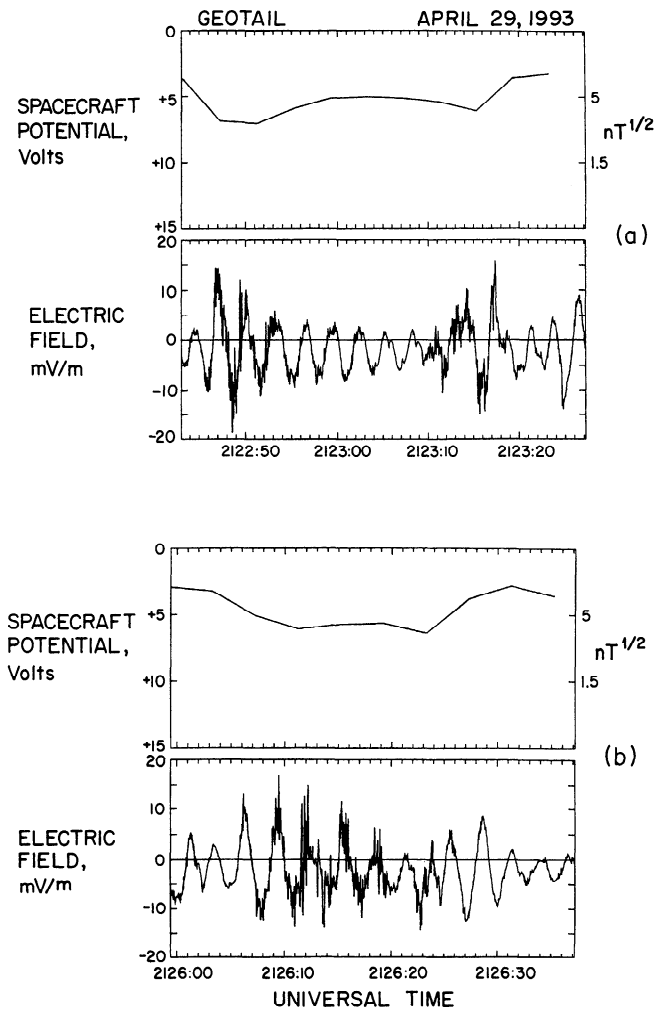
## 4. Discussion

### 4.1. Calculations of Resistivity

In order to assess the probable importance of waves with the observed amplitudes and frequencies on the



**Figure 3.** Electric and magnetic field data obtained during magnetopause crossings on April 29, 1993, by the Geotail spacecraft. (a) the spacecraft potential (proportional to the plasma density); (b) the electric field along the spinning boom; (c)-(f) the magnitude and three components of the magnetic field in GSE; and (g) is the standard deviation in the least squares fit to the electric field. Expanded views of the raw electric field at two times are shown below.



**Figure 4.** The raw electric field and the spacecraft potential at two times are plotted to show the wave amplitude dependence on density and density variations. An approximate density scale [Mozer *et al.*, 1994] is indicated.

physical processes occurring within the magnetopause and adjacent regions, two different quasi-linear calculations will be discussed. The first, based on Gary [1980], provides an estimate of the resistivity due to lower hybrid drift waves; the second [Coroniti, 1985] yields a critical amplitude for the electric field needed for fast reconnection to occur. In both calculations, the following values of the parameters are used:  $T_i/T_e \sim 10$ ,  $B \sim 30\gamma$ ,  $T_e \sim 40$  eV,  $n \sim 20$  cm $^{-3}$ ,  $E \sim 20$  mV/m. The plasma values are based on the ISEE observations. Gary [1980] calculated the anomalous resistivity which could be provided by various wave modes assuming quasi-linearity. For the lower hybrid drift instability, this resistivity is given by

$$\eta \approx \frac{(8\pi)^{1/2}(1 - 0.3(T_i/T_e)^{1/4})}{(1 + T_i/T_e)} \left( \frac{1}{f_{LH}} \right) \left( \frac{|E|^2}{nT_e} \right).$$

For the parameters given above, this yields a resistivity of  $\eta \approx 7 \times 10^4$  s which is many orders of magnitude larger than the classical value and is large enough to provide the required dissipation. Coroniti [1985] estimated the critical amplitude of lower hybrid drift waves, assuming a gradient scale length,  $\lambda$ , equal to the ion gyroradius, as follows:

$$(\delta E_{cr})^2 \approx M_A \left( \frac{V_A}{c} \right) \left( \frac{f_{LH}}{f_{pi}} \right) \left( \frac{2\pi\lambda f_{pi}}{c} \right) (8\pi n_e T_e).$$

Using the above parameters,  $(\delta E_{cr})^2 \approx 10^{-5}$  V $^2$ /m $^2$ . Since  $(\delta E_{obs})^2 \approx 4 \times 10^{-4}$  V $^2$ /m $^2$ , we find that

$$\frac{(\delta E_{obs})^2}{(\delta E_{cr})^2} \approx 40.$$

This method also shows that the observed wave electric fields are often larger than that needed to produce dissipation. Note that, although both calculations utilized an electric field of 20 mV/m which is near the high end of observed waves, the more typical wave amplitudes are also above the critical value.

## 4.2. Conclusions

It has been shown from ISEE 1 electric field data that waves below the lower hybrid frequency are observed in the same region at the same time as the occurrence of quasi-steady state reconnection could be inferred from magnetic field and plasma measurements. The waves were generally more intense when  $\beta$  was lower. Both the wave frequency and the amplitude dependence on  $\beta$  are consistent with theories of lower hybrid drift waves.

Data from subsolar crossings of the magnetopause by the Geotail spacecraft also show intense waves below the lower hybrid frequency. These data provided evidence that the wave were often most intense near density gradients and in regions of low density (low  $\beta$ ). At times, large spiky fields were also embedded in the lower amplitude linear waves. These spikes may be due to the nonlinear evolution of the waves.

Two different quasi-linear calculations indicated that the observed amplitudes are often large enough to provide the dissipation required for reconnection to occur. These observations are very similar to those in the plasma sheet. In a study of the waves during a period identified as a near-Earth neutral line occurring near the satellite, Cattell and Mozer [1986, 1987] showed that there were lower hybrid drift waves intense enough to provide the necessary resistivity. Mozer *et al.* [1985] presented examples of the associated large spiky fields.

Future studies will examine the polarization and wave number, as well as the amplitude and frequency distributions, of the waves observed at the magnetopause.

**Acknowledgments.** The authors thank C. T. Russell for use of the ISEE 1 magnetometer data, and the entire Japanese Geotail team. The ISEE work was supported by NASA contract NAG5-375, Dartmouth subcontract 5-36512 of NASA contract NAG5-1098, and the Geotail work by NASA NAS5-30241.

The Editor thanks R.A. Treumann and M.F. Smith for their assistance in evaluating this paper.

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(Received July 21, 1994; revised November 22, 1994;  
accepted November 29, 1994.)