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Geotail observations of low-frequency waves from 0.001 to 16 Hz during the November 24, 1996, Geospace Environment Modeling substorm challenge event

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Abstract. We present observations of low-frequency waves from 0.001 Hz up to the lower hybrid frequency during the time periods corresponding to the growth, expansion, and recovery phases of a substorm that occurred from ~ 2100 to 2310 UT on November 24, 1996, while Geotail was located in the magnetotail at X_{GSE} ~ 25 R_E and 0100 LT. Large-amplitude waves near the lower hybrid frequency were observed when large-scale density and magnetic field gradients were present during thinning of the plasma sheet at substorm onset and the beginning of the recovery phase. Later in the recovery phase, waves near the lower hybrid frequency were observed close to the neutral sheet in localized areas with strong small-scale density and magnetic field gradients. Fluctuations of the electric and magnetic fields near the ion gyrofrequency were also observed during this event; however, the amplitudes were smaller than those often observed in the near tail in association with substorms. Compressional fluctuations of the magnetic field in the Pi2 frequency range were observed close to substorm onset. Although Geotail was not in the region considered in recent studies of Pi2 pulsations, it may still be possible that the magnetic field fluctuations observed by Geotail during the November 24, 1996, substorm are related to this phenomenon since little is known about propagation of the compressional pulses and generation of the waves.

1. Introduction

The Geospace Environment Modeling (GEM) Substorm Working Group selected an isolated substorm on November 24, 1996, which occurred from ~ 2100 to ~ 2310 UT as the focus for intensive study and testing of substorm models by the GEM community. During this substorm the Geotail satellite was located at X_{GSE} ≈-25 R_E near 0100 LT. To examine the large-scale processes occurring in the magnetotail during this substorm, *Petrukovich et al.* [1998] compared the magnetic pressure observed by Geotail in the equatorial plasma sheet and Interball-Tail in the high-latitude tail lobe at a radial distance of ~ 26 R_E. The substorm growth phase began at ~ 2108 UT with a southward turning of the interplanetary magnetic field (IMF) observed by Wind. Interball-Tail and Geotail observations by Petrukovich et al. indicated thinning of the plasma sheet from 2108 to 2200 UT. A brief enhancement of the pressure occurred around 2148 UT, at the same time a pseudobreakup was recorded by ground magnetometers. The total pressure observed by Geotail in the equatorial plane peaked between 2225 and 2236 UT, at the onset of the expansion phase. A minimum in the pressure was observed at 2307 UT, indicating the start of the recovery phase. Petrukovich et al. interpreted their pressure and velocity measurements as an indication that the substorm activation region formed earthward of Geotail and that the x-line was located near the satellite toward the end of the expansion phase. The relation between the magnetotail current and pressure during this substorm was considered by *Jacquey et al.* [1998] using data from Interball-Tail and IMP 8. Both satellites observed an increase in the lobe magnetic pressure during the growth phase, followed by a decrease in the lobe magnetic pressure by the same amount during the expansion phase. Because the solar wind dynamical pressure obtained from Wind data was nearly constant during the growth phase, the initial increase in tail lobe pressure was interpreted by Jacquey et al. to have been caused by an internal process, such as an intensification in the cross-tail current.

In this paper we will examine the low-frequency waves from 0.001 to 16 Hz that occurred in the magnetotail during the November 24, 1996, substorm using electric and magnetic field data from Geotail. Waves in this frequency range have been shown to be present throughout the near tail and midtail during substorms (Sigsbee et al., manuscript in preparation, 2000; T. Streed et al., Spiky electric fields in the magnetotail, submitted to *Journal of Geophysical Research*, 2000, hereinafter referred to as Streed et al., submitted manuscript, 2000). In the near-tail, low-frequency electric and magnetic field fluctuations may play important roles in the generation of Pi2 pulsations. The production of Pi2 pulsations is not well understood, but attempts have been made to associate Pi2 pulsations with other phenomena that occur in the magnetotail at substorm onset, such as magnetic reconnection and earth-

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ward flows. Recent theories of Pi2 pulsations have proposed that they are generated by compressional pulses produced by high-speed earthward flows in the near tail [*Shiokawa et al.*, 1998; *Kepko and Kivelson*, 1999]. Geotail was located at a radial distance of 25 R_E and 0100 LT during the November 24, 1996, substorm, outside of the regions considered in recent studies of Pi2 generation. However, little is known about how compressional pulses produced by earthward flow bursts or magnetic reconnection might propagate through the magnetotail. Examination of fluctuations in the Pi2 frequency range during the November 24, 1996, substorm may help clarify this issue.

In the near tail, waves close to the ion gyrofrequency are important to the current disruption model, in which substorm onset is caused by a cross-field current instability that excites waves at the neutral sheet and results in disruption of the cross-tail current [*Lui*, 1996]. The current disruption model is an alternative to the near-Earth neutral line model and suggests that substorm onset is caused by a process in the near tail, rather than magnetic reconnection at a near-Earth neutral line. We will also study waves near the ion gyrofrequency during the November 24, 1996, substorm, in order to examine the possibility that a cross-field instability of the type considered in the current disruption model operates in magnetotail at radial distances of 25 R_E.

Waves near the lower hybrid frequency in the midtail region have been proposed as a possible source of anomalous resistivity for magnetic reconnection at a near-Earth neutral line. The free energy to drive the lower hybrid drift instability comes from the cross-field current and gradients in the plasma and magnetic field, which are an integral part of the process of magnetic reconnection [*Huba et al.*, 1977]. A number of studies have attempted to determine where magnetic reconnection occurs in the magnetotail during substorms. In a survey of ISEE 1 data, *Cattell and Mozer* [1984] found evidence that the neutral line forms in the region $X_{GSM} < -21$ R_E, $|Y_{GSM}| < 4.5$ R_E, and $|Z_{GSM}| < 3$ R_E. Recent work with Geotail data has shown that reconnection usually starts in the premidnight sector of magnetotail between $X_{GSM} = -20$ R_E and $X_{GSM} = -30$ R_E a few minutes before the substorm onset is observed on the ground as Pi2 pulsations [*Nagai et al.*, 1998]. Another study of Geotail data has shown the location of the neutral line to be near $X_{GSM} = -20$ R_E and $Y_{GSM} = 5$ R_E [*Machida et al.*, 1999]. During the November 24, 1996, event, Geotail was located near $X_{GSE} = -25$ R_E, $Y_{GSE} \approx -8$ R_E, and $Z_{GSE} \approx -3$ R_E (01:00 LT), outside the region where reconnection is usually thought to occur during substorms. It is unlikely that the low-frequency waves observed by Geotail during this event were related to magnetic reconnection at the near-Earth neutral line. However, the observation of waves near the lower hybrid frequency during the November 24, 1996, substorm is still of significant interest because lower hybrid waves in the magnetotail may cause ions to exhibit nonadiabatic, chaotic motion and could provide a source of ion energization [*Cattell et al.*, 1995; Streed et al., submitted manuscript, 2000].

2. Low-Frequency Waves in the Magnetotail

Pi2 pulsations (0.007-0.03 Hz) have long been considered an important indicator of geomagnetic activity, particularly for determining substorm onset times. One recent theory about Pi2 pulsations proposes that they are generated by a compressional pulse produced when high-speed earthward flows are braked at the boundary between taillike and dipolar magnetic field regions [*Shiokawa et al.*, 1998]. At the braking point of the flow, the increase in earthward kinetic pressure due to the flow can compress the inner magnetosphere, resulting in a compressional pulse. This disturbance may propagate across the equatorial magnetic field and couple into a cavity mode oscillation and/or propagate along the field as an Alfvén wave to the high-latitude ionosphere [*Yumoto et al.*, 1989]. Another possible generation mechanism for Pi2 pulsations in the scenario proposed by *Shiokawa et al.* [1998] are fluctuations of the induced field-aligned currents at the braking point. In support of this hypothesis, Shiokawa et al. observed compressional pulses with periods between 40 and 160 s in Active Magnetospheric Particle Tracer Explorers (AMPTE)/CCE magnetic field data associated with high-speed earthward flows during a substorm. A similar idea was developed by *Kepko and Kivelson* [1999], who presented observations from ISEE 2, the Institute of Geological Sciences (IGS) magnetometer chain, and the Air Force Geophysical Laboratory (AFGL) magnetometer chain relating bursty bulk flows in the magnetotail to Pi2 pulsations. They found a one-to-one correlation between earthward flow bursts in the magnetotail and the onset of Pi2 pulsations at various ground stations. The correlations between oscillations observed by the AFGL magnetometers and variations of the earthward flows led Kepko and Kivelson to propose that the frequencies of low-latitude Pi2 pulsations are determined by temporal variations of earthward flows in the magnetotail.

Waves near the ion gyrofrequency, which typically is between ~ 0.1 and 1.0 Hz in the near tail and midtail, could be excited by a cross-field current instability of the type discussed by *Lui* [1996]. The cross-field current instability (CFCI) considered by Lui is a collective term for the lower hybrid drift instability, the modified two-stream instability, and the ion-Weibel instability. The CFCI is directly driven by current flow across the tail and operates over a broad frequency spectrum ranging from the lower hybrid drift frequency down to the ion gyrofrequency or lower. In the near-tail region this instability has been proposed to play a crucial role in the current disruption model. This model of substorms suggests that substorm onset is caused by a cross-field current instability that excites waves near the ion gyrofrequency at the neutral sheet near the inner edge of the cross-tail current. The instability results in disruption of the magnetotail current in the near-Earth region, generation of field-aligned currents, and formation of the substorm current wedge. Observational evidence for this instability in the near-tail region comes from AMPTE/CCE observations between 7.4 and 8.8 R_E of low-frequency waves from 0.1 to 4 Hz close to the ground onset times of substorm expansions or intensifications [*Lui et al.*, 1992]. An instability of this kind could provide a possible source of dissipation for magnetic reconnection and particle energization in other regions of the magnetotail.

Many observations have been made of waves near the lower hybrid frequency in the magnetotail. ISEE 1 electric field observations of lower hybrid drift waves in the magnetotail were presented by *Cattell and Mozer* [1987] during a time period when a neutral line moved past the satellite. Large-amplitude (> 30 mV/m) waves at approximately half the lower hybrid frequency (consistent with the lower hybrid drift instability) were observed throughout the plasma sheet during this substorm. The waves were found from the plasma sheet boundary layer to the neutral sheet and occurred simultaneously with large DC fields and **ExB** velocities associated with the near-Earth neutral line. Theoretical work has suggested that waves associated with the lower hybrid drift instability should be suppressed at the neutral sheet owing to the large plasma β in this region. However, Cattell and Mozer found that the largest waves occurred near the neutral sheet when the southward component of the magnetic field was 6 nT, so β remained < 1.

Lower hybrid waves in the magnetotail are often associated with large, spiky electric fields. Low-frequency turbulence and large electric field spikes up to ~ 80 mV/m were observed in ISEE 1 data from distances of 7-23 R_E within 4 hours of midnight [*Cattell et al.*, 1982]. Similar observations have been made by Geotail in the plasma sheet and plasma sheet boundary layer at radial distances between 40 and 90 R_E [*Cattell et al.*, 1994]. The collapse of large-amplitude lower hybrid drift waves through a wave-wave interaction that causes nonlinear wave growth may be responsible for these spiky electric fields [*Shapiro et al.*, 1993]. An alternate explanation for the spiky electric fields was suggested by recent work with data from the Polar satellite showing small scale, large-amplitude kinetic Alfvén waves at the plasma sheet boundary (J. R. Wygant et al., Evidence for kinetic Alfvén waves and parallel electron energization at the high altitude plasma sheet, submitted to *Geophysical Research Letters*, 2000). A statistical study of the occurrence of waves near the lower hybrid frequency and large, spiky electric fields in the magnetotail between radial distances of 10 and 200 R_E was performed by Streed et al. (submitted manuscript, 2000) using Geotail electric field data. Waves near the lower hybrid frequency and electric field spikes were found throughout the plasma sheet up to distances of 100 R_E and had a tendency to occur in large density gradients. Simulations of the effects of lower hybrid waves on ion trajectories in the magnetotail have shown that interactions between ions and the waves can drastically alter the ion trajectories and result in energization of the ions [*Cattell et al.*, 1995]. Simultaneous observations by Geotail of waves near the lower hybrid frequency in the plasma sheet boundary layer at 69 R_E and particle measurements showing an increase in the ion energy from 0.1 to 10 keV/e were presented by *Okada et al.* [1994]. These observations were interpreted as evidence that the cold ions in the plasma sheet boundary layer were being heated by the waves. As demonstrated by the observations and models discussed here, lower hybrid drift waves could be a significant source of heating within the magnetotail out to radial distances of 100 R_E.

3. Data Sets and Analysis Methods

The electric field data presented in this paper were obtained from the Geotail spherical double-probe electric field instrument [*Tsuruda et al.*, 1994], which measures the electric field in the spin plane of the spacecraft. It consists of a pair of 50-m wire booms with 105-mm diameter spherical probes on each end deployed perpendicular to the spacecraft spin axis. The spacecraft potential, or voltage difference measured between one of the spherical probes and the spacecraft, can provide an estimate of the plasma density and temperature. The spacecraft potential is a balance between the photoelectron current from the spacecraft and the incoming electron current; this potential is roughly proportional to $\ln(nT^{1/2})$ [*Pedersen*, 1995]. Although an exact density calibration for the spacecraft potential in the region of the magnetotail discussed in this paper is not available, the spacecraft potential can still be used to identify entry into and exit from different magnetospheric regions.

By measuring the potential difference between the two spherical probes and dividing by the distance between them (100 m), a measurement can be made of the electric field. In this paper the electric field measurements across the spinning booms of the spacecraft sampled at 32 points per second (editor-B format) were used to examine waves up to 16 Hz. Because of Geotail's rotation about its spin axis, the electric field exhibits a 3-s sinusoidal modulation. Also, because the photoelectron density is higher on the sunlit side of the spacecraft, a spurious sunward electric field is produced twice each spin period. To eliminate the sinusoidal spin modulation and harmonics, the 32 samples per second data were filtered to remove frequency components below 2 Hz. The 32 samples per second electric field data were analyzed using a windowed fast Fourier transform (FFT) to search for bursts of waves near the lower hybrid frequency. Despun electric field data at 3-s resolution, corresponding to the X and Y components of the electric field in GSE coordinates, were used to study fluctuations from 0.001 Hz up to 0.16 Hz, which includes the frequency ranges of the Pi1-Pi2 and Pc2-Pc5 classes of ULF pulsations. The continuous Morlet wavelet transform [*Kumar and Foufoula-Georgiou*, 1994, and references therein] was used to analyze the Geotail 3 second spin fit electric field data. The Morlet wavelet transform was the preferred method of analysis for the 3-s resolution data because it provided better temporal and frequency resolution at the lowest frequencies than the FFT. The traditional FFT analysis method was preferred to study the high-resolution 32 samples per second electric field data mainly because it was more computationally efficient.

Data from the Geotail magnetic field experiment [*Kokubun et al.*, 1994] were also used to study low-frequency waves in the magnetotail. Because the magnetometer makes a full three-dimensional measurement at 16 samples per second, waves up to the Nyquist frequency (8 Hz), including waves near the spin frequency (0.333 Hz), can be studied with the magnetic field data. This is important because the ion gyrofrequency typically falls between 0.1 and 1.0 Hz, a frequency range which is often totally dominated by spin harmonics in the electric field data. The 3-s spin averaged magnetic field data were used to examine fluctuations below 0.16 Hz, while the high-resolution magnetic field data were used to examine fluctuations near the ion gyrofrequency from ~ 0.01 Hz up to 1 Hz. The Morlet wavelet transform was the preferred method of analysis for the 3-s resolution and 16 samples per second resolution magnetic field data.

4. Growth Phase

An overview of Geotail 3-s electric and magnetic field data and the spacecraft potential from 2030 to 2340 UT, covering the entire time span of the substorm, is shown in Figure 1. From 2030 to 2100 UT, prior to the start of the growth phase, Geotail was located in the plasma sheet, as indicated by the spacecraft potential. Fluctuations of the electric field and magnetic field were observed starting around 2100 UT, close to the beginning of the growth phase at 2108 UT. Because the fluctuations observed during the growth phase actually started before the southward turning of the IMF, they were probably remnants of earlier activity or the result of some local process in the magnetotail. The fluctuations continued until ~ 2120 UT. The pseudobreakup observed in ground magnetometer data and indicated by a pressure increase at Geotail at 2148 UT [*Petrukovich et al.*, 1998] also appeared as a brief thinning of the plasma sheet, as shown by an increase in the magnitude of the spacecraft potential.

Wavelet scalograms [e.g., see *Rioul and Flandrin*, 1992] of the 3-s electric and magnetic field data from 2030 to 2340 UT are shown in Plate 1. From 2100 to ~ 2120 UT, peaks appear in the wavelet scalograms from 0.01 Hz up to the Nyquist

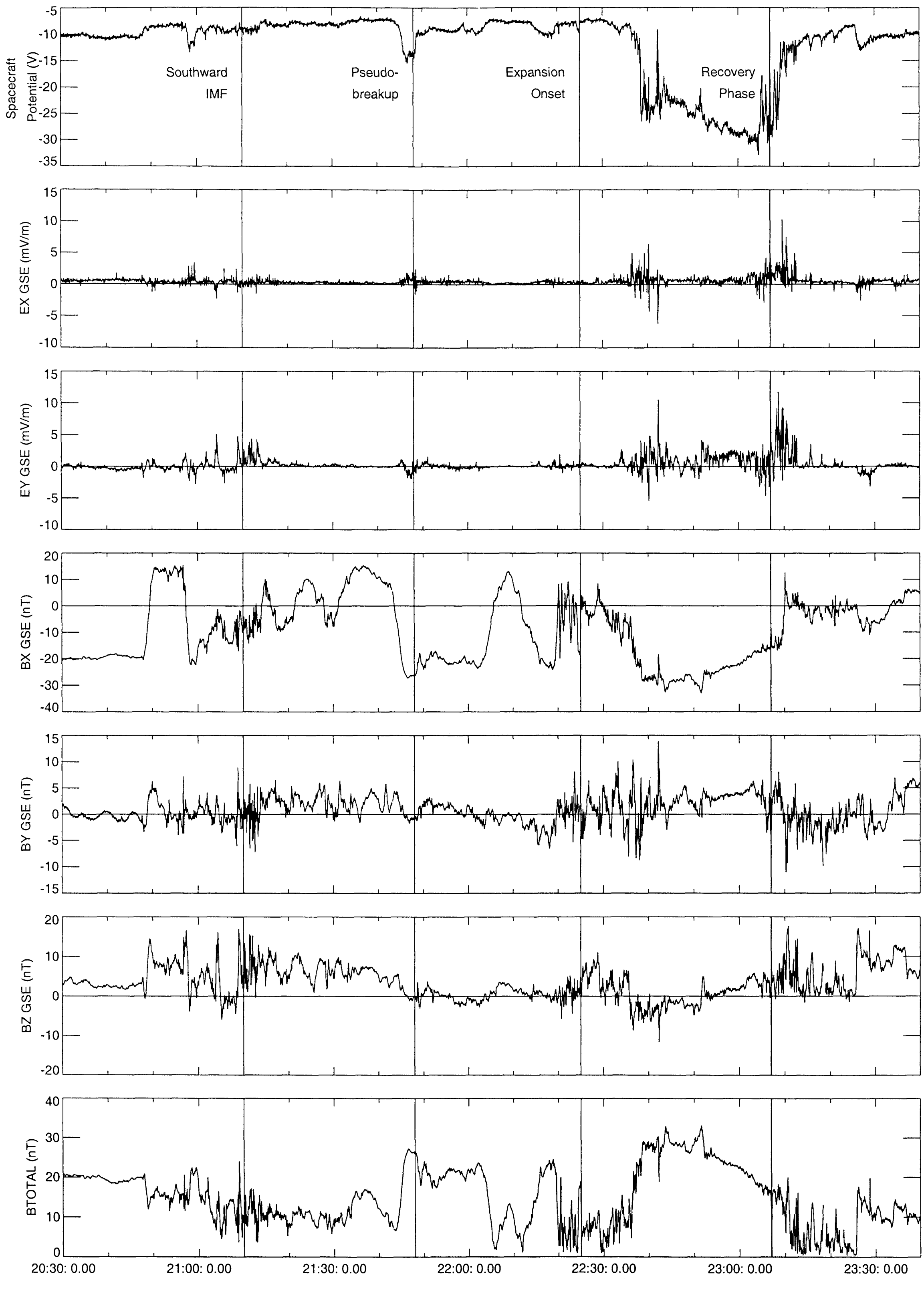

Figure 1. Overview of Geotail data from the November 24, 1996, substorm, showing the negative of the spacecraft potential, the 3-s electric and magnetic field data in GSE coordinates, and the total magnetic field. The negative of the spacecraft potential is shown so that smaller values indicate lower densities, while larger values indicate higher densities. The times of the southward turning of the interplanetary magnetic field (IMF), pseudobreakup, expansion onset, and recovery phase from *Petrukovich et al.* [1998] are marked by vertical lines.

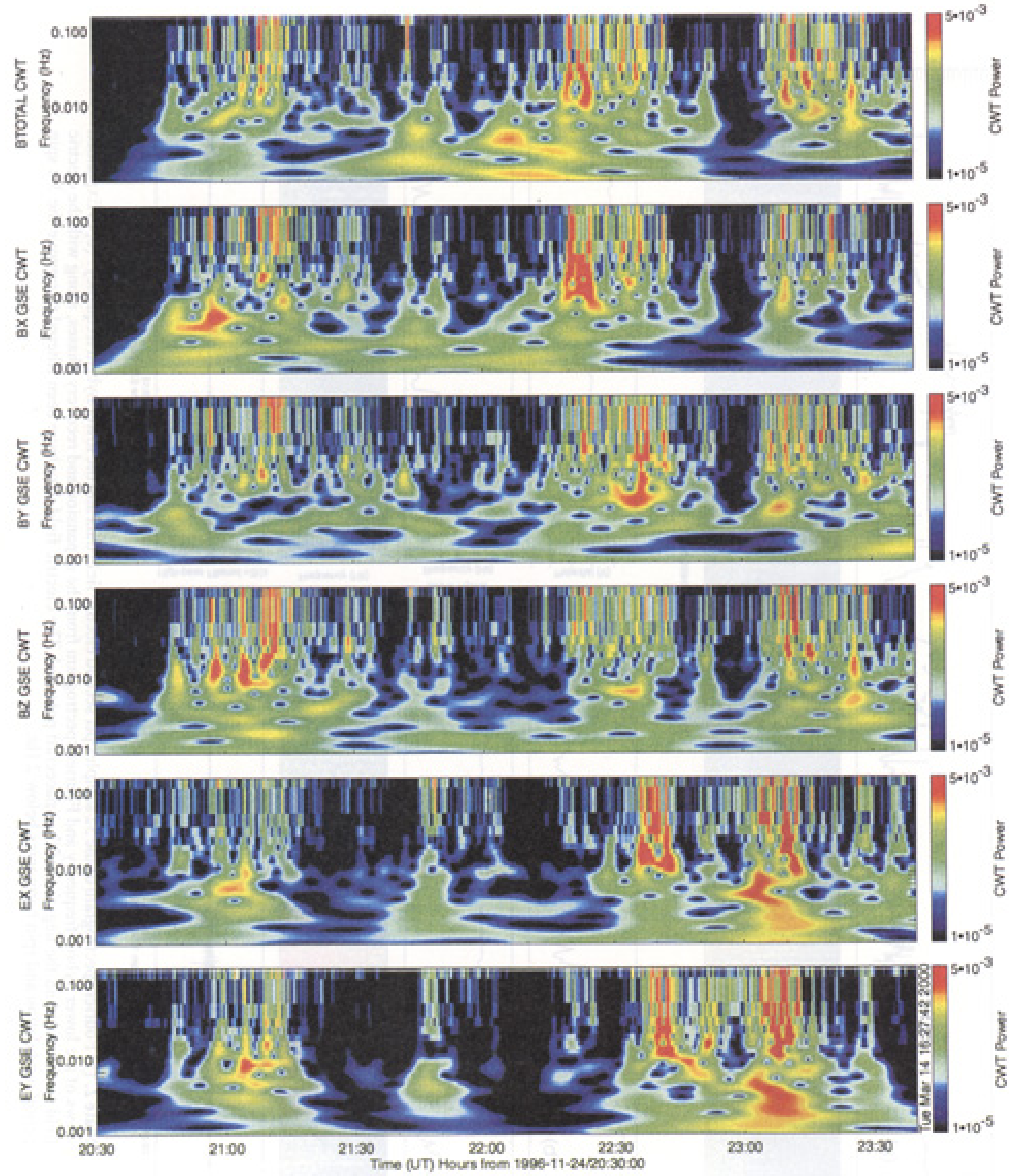

Plate 1. Wavelet scalograms of the 3-s electric and magnetic field data in GSE coordinates from 0.001 Hz up to the Nyquist frequency, 0.16 Hz, for the same time period as that shown in Figure 1.

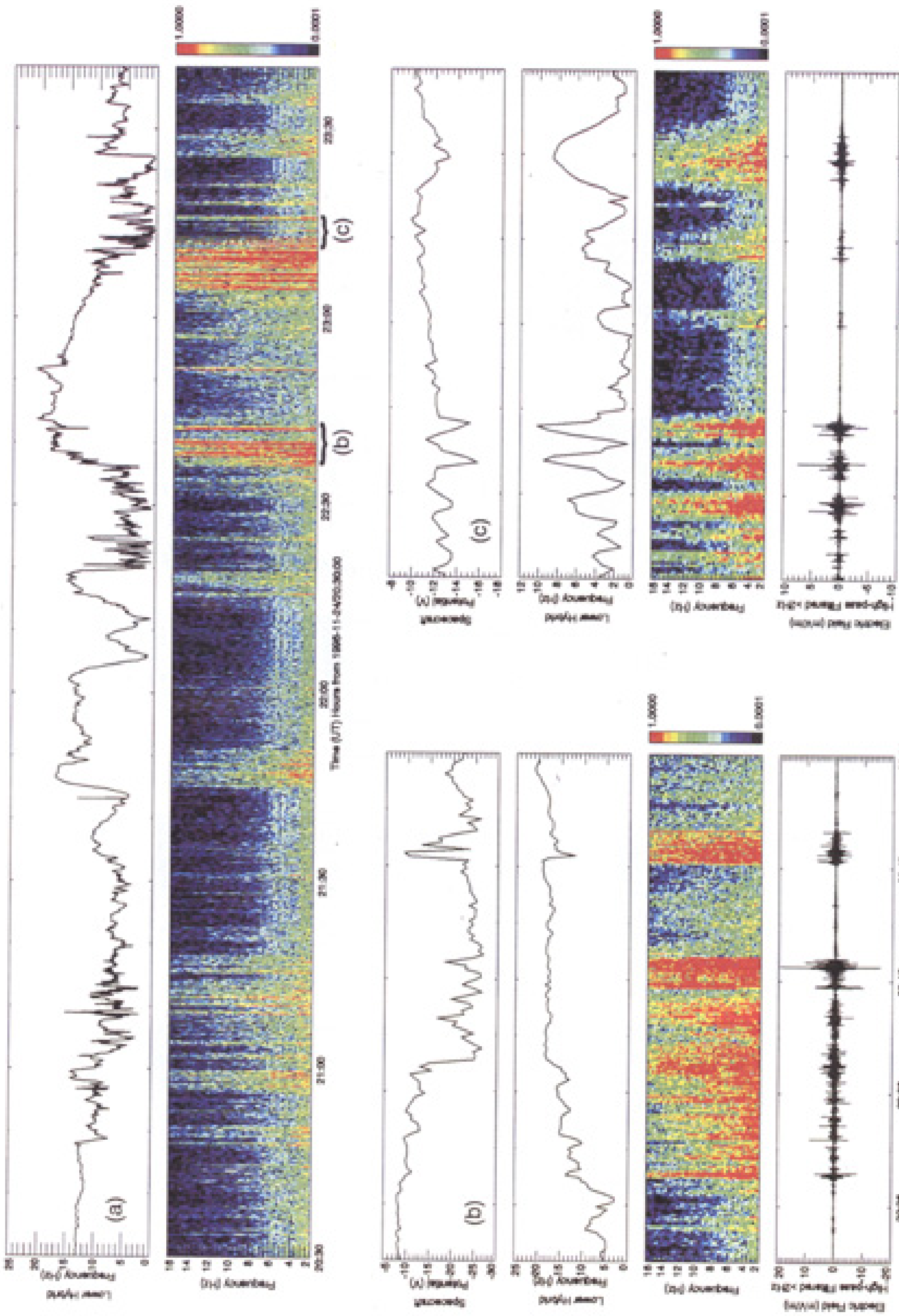

Plate 2. (a) Fourier spectrogram of the 32 samples per second electric field data and the lower hybrid frequency. (b, c) Expanded views of the lower hybrid frequency and Fourier spectrogram from the expansion and recovery phases, along with the electric field waveforms and the negative of the spacecraft potential. The electric field data have been filtered to remove the 3-s spin period modulation and spin harmonics below 2 Hz.

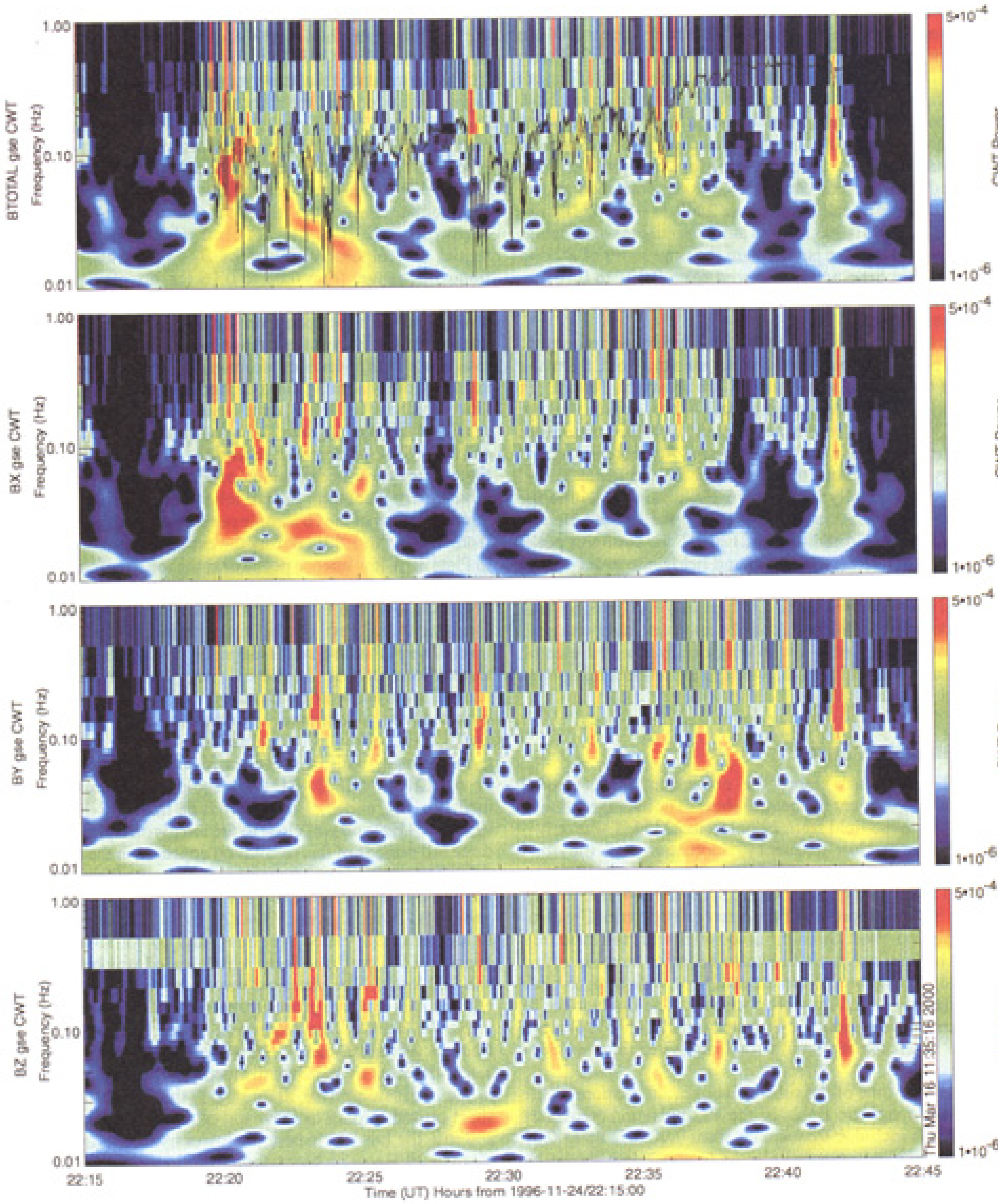

Plate 3. Wavelet scalograms of the high resolution (16 samples per second) magnetic field data in GSE coordinates from 0.01 to 1.0 Hz. The time period shown covers the onset of the expansion phase. The ion gyrofrequency has been plotted as a black line over the scalogram of the total magnetic field.

frequency for the 3-s data, which is 0.16 Hz. A series of three bipolar pulses visible in the times series of B_Z also appear near 0.01 Hz in the scalogram of B_Z from 2035 to 2105 UT. The first two of the pulses in B_Z are clearly associated with large changes in B_X as the spacecraft crossed the current sheet. A peak associated with this spatial structure appears in the scalogram of B_X near 0.004 Hz from 2050 to 2100 UT. Strong peaks from 0.01 Hz up to 0.16 Hz occur at ~ 2110 UT in all three components of the magnetic field and the electric field. During the growth phase, many of the peaks in the scalograms below 0.01 Hz appear to be correlated with the passage of spatial structures over the satellite, for example, the peak associated with the current sheet crossing described above. One exception is a peak lasting from 2040 to ~ 2155 UT in B_Y between 0.002 and 0.003 Hz. An almost sinusoidal oscillation in this frequency range is visible in the time series of B_Y. At 2148 UT, very little activity is seen from 0.001 to 0.16 Hz, except for peaks associated with a crossing of the current sheet at this time.

The lower hybrid frequency and a Fourier spectrogram of the filtered 32 samples per second electric field from the spherical double probe instrument are shown in Plate 2. In this region of the magnetotail the approximation $f_{LH} \approx (f_{ce} f_{ci})^{1/2} \approx 0.65 \mathrm{x} B$, where the magnetic field is in nanoteslas and the frequency is in hertz, can be used for the lower hybrid frequency. Throughout the growth phase the lower hybrid frequency was usually less than 16 Hz, placing it within the frequency range that can be detected by the Geotail electric field instrument. From 2050 to 2120 UT the strongest peaks in the spectrogram are seen near and below the lower hybrid frequency, which ranged between 2 and 14 Hz. The waves observed from 2050 to 2120 UT typically had peak to peak amplitudes of a few mV/m. A brief wave burst, also with peak to peak amplitudes of a few mV/m, occurred in the electric field data around 2150 UT, when the pseudobreakup was observed.

5. Expansion Phase

At 2220 UT, just before the expansion onset, Geotail entered the region near the neutral sheet. The average value of the total magnetic field from 2220 UT to 2235 UT was only ~ 7 nT; however, low-frequency fluctuations of the total magnetic field with amplitudes greater than10 nT were observed during this time. At 2235 UT there was a sudden increase in the magnitude of the spacecraft potential, indicative of plasma sheet thinning associated with the substorm onset. The total magnetic field also began to increase at this time, and fluctuations of the electric field with peak to peak amplitudes of ~30 mV/m were observed. The fluctuations of the electric and magnetic fields lasted until 2245 UT, close to the time when the maximum total magnetic field was observed.

Around the time of the substorm onset, fluctuations of the electric and magnetic fields in the Pi2 pulsation frequency range, which includes frequencies from 0.007 Hz up to 0.03 Hz, were observed. Geotail plasma moment data shown by *Petrukovich et al.* [1998] indicated strong earthward flows of a few hundred km/s between 2214 and 2228 UT, and short bursts of both earthward and tailward flow from 2228 to 2240 UT. Although some of the fluctuations observed in the Pi2 frequency range are compressional and are associated with earthward flow, it is not always clear whether or not these fluctuations are actually associated with Pi2 pulsations or are related to spatial structures visible in the time series data. The most likely candidates for fluctuations associated with Pi2 pulsations are strong peaks that appeared in the scalograms of the 3-s B_X and B_{TOTAL} from 0.008 Hz up to 0.03 Hz at 2220 UT. These peaks are similar to those seen in the near-tail at substorm onset (Sigsbee et al., manuscript in preparation, 2000), but are smaller in amplitude. Polarization analysis of the 3-s magnetic field data using the method described by *Samson and Olson* [1980] was inconclusive. Analysis by this technique indicated that these magnetic field fluctuations were highly polarized, but the direction was not well determined. From 2230 to 2240 UT peaks were seen in the scalogram of B_Y near 0.005 Hz, corresponding to a sinusoidal variation visible in the B_Y time series data. Although the oscillation in B_Y occurred at a frequency just below the Pi2 frequency range and began around the time of onset, it is not strongly compressional. It is also not clear whether or not this is a spatial or temporal variation of B_Y. Peaks above the Pi2 frequency range, from 0.03 to 0.16 Hz, are also seen in the scalograms of all three components of the magnetic field throughout the time span from 2220 to 2240 UT. However, the power in this frequency range is very bursty. Fluctuations in all three components of the magnetic field and both components of the magnetic field ceased shortly after 2240 UT, when thinning of the plasma sheet left Geotail in a quiet region of taillike magnetic field and relatively low density, as shown by the spacecraft potential. This agrees with the Geotail pressure observations of *Petrukovich et al.* [1998], which place Geotail in the tail lobe at this time.

Scalograms of the 16 sample per second magnetic field data from 0.01 Hz to 1.0 Hz during the expansion phase are shown in Plate 3. A few intense peaks near the ion gyrofrequency are seen from 2220 to 2225 UT, just before the expansion onset. Peaks close to the ion gyrofrequency are seen sporadically throughout the rest of the time period shown. A visual inspection of the time series magnetic field data shows that the fluctuations in this frequency range are generally a few nanoteslas in amplitude. During the expansion phase the ion gyrofrequency occasionally dropped to values between 0.01 and 0.1 Hz, allowing examination of waves near the ion gyrofrequency with the 3-s electric and magnetic field data. From 2221:40 to 2222:40 UT a sinusoidal oscillation appeared in B_{TOTAL}, B_Z, and E_Y. The oscillation had a 12-13 s period (0.07-0.08 Hz) and was close to the ion gyrofrequency. About three full periods of this oscillation appeared in the time series data. The oscillations of E_Y and B_Z were undersampled and were in phase with peak to peak amplitudes of ~ 0.5 mV/m and ~ 4 nT, which gives E/B ~ 125 km/s. The total magnetic field at this time varied between 5 and 10 nT, so assuming a density of 0.5 cm^{-3}, the local Alfvén speed was between 150 and 300 km/s. The observed waves are therefore consistent with an Alfvén wave propagating in the X direction.

At the start of the expansion phase, the lower hybrid frequency was less than 16 Hz, within the frequency range that can be detected by the Geotail electric field instrument. Later in the expansion phase, at 2235 UT, thinning of the plasma sheet caused Geotail to move out of the central plasma sheet and into the tail lobe where the lower hybrid frequency was close to 20 Hz. The spectrogram in Plate 2 shows that from 2236 UT to 2243 UT very intense waves from 2 Hz up to 16 Hz are seen at the same time as the sharp gradients in the magnetic field and spacecraft potential. The Fourier spectrogram from 2235 UT to 2244 UT in Plate 2b shows that as the lower hybrid frequency increased from 4 to ~ 18 Hz, the frequency of the waves seen in the electric field data also increased. The amplitudes of the waves seen during this time period typically had peak to peak amplitudes of ~ 10 mV/m, but larger-amplitude fluctuations > 20 mV/m were seen briefly near 2240 UT. The large-amplitude fluctuations abruptly stopped at 2240:30, when the total magnetic field leveled off at ~ 29 nT. One last burst of waves from 2 to 16 Hz occurred at 2242 UT when the total magnetic field suddenly dropped to 18 nT and then returned to its previous value. A momentary increase in the local density also occurred at this time, as shown by the spacecraft potential in Plate 2b. The waves seen during this brief burst had amplitudes of ~ 10 mV/m. From 2242 UT to the start of the recovery phase, no wave activity was observed while Geotail remained in the tail lobe. Although the plasma β is low in the tail lobe, the absence of lower hybrid waves in this region is expected, because other conditions are unfavorable for this mode. The lobes are typically characterized by quiet, taillike magnetic fields and a lack of strong gradients, which are needed for the growth of lower hybrid drift waves. The lower hybrid drift instability is driven by the cross-field current associated with the magnetic field reversal, so this mode should not be present outside the magnetotail current sheet.

6. Recovery Phase

The plasma sheet began to recover at ~ 2305 UT, as indicated by a sudden decrease in the magnitude of the spacecraft potential to approximately its preonset value. A corresponding decrease in the magnitude of the magnetic field was also observed, and Geotail once again entered the vicinity of the neutral sheet. Fluctuations of the electric and magnetic fields with amplitudes comparable to those seen at the onset of the expansion phase were seen at the start of the recovery phase. However, during the recovery phase the nature of these fluctuations was ambiguous. Many of the lowest frequency peaks in the wavelet scalograms appear to be correlated with large DC electric fields and earthward **E**x**B** flows seen at this time. The magnetic field continued to fluctuate until ~ 2330 UT; however, the electric field fluctuations decreased dramatically in amplitude at ~ 2312 UT, which was about the same time as the steep gradients in the magnetic field and spacecraft potential disappeared.

During the recovery phase, intense waves from 2 to 16 Hz, both above and below the lower hybrid frequency, occurred between 2304 and 2314 UT. The waves occurred during the time period when the plasma sheet recovered and the magnetic field decreased from 20 nT to a few nanoteslas. The amplitudes of the waves seen during this time period were comparable to the amplitudes seen during the thinning of the plasma sheet in the expansion phase. After 2310 UT, Geotail was located quite close to the neutral sheet. The average total magnetic field value from 2310 to 2325 UT was ~ 5 nT, but the total magnetic field fluctuated in this region, often dropping close to zero or increasing to greater than 10 nT. One of the major criticisms of the interpretation of observations of waves below the lower hybrid frequency in the magnetotail is that the quasi-linear theory of the lower hybrid drift instability shows that this mode is stabilized near magnetic neutral regions because as $B \to 0$, we also have $\beta \to \infty$. As illustrated by the data presented in Plate 2c, the waves are indeed suppressed during times when the total magnetic field is less than ~ 2-3 nT. However, bursts of waves close to the lower hybrid frequency with amplitudes of a few mV/m occurred during times when the total magnetic field briefly increased by a few nanoteslas.

Plate 2c shows a series of wave bursts that occurred close to the neutral sheet during time periods when B_Z increased briefly to values between ~ 7 and 15 nT. The fluctuations of B_Z and associated wave bursts from 2311 to 2313 UT appear to be periodically spaced on a timescale of ~ 25 s. Corresponding peaks appear in E_Y, indicating that each wave burst may have also been associated with short bursts of earthward **E**x**B** flow. The plasma moment data shown by *Petrukovich et al.* [1998] also indicated earthward flow at this time. The electric and magnetic field fluctuations were associated with fluctuations in the magnitude of the spacecraft potential that indicate local decreases in the plasma density during the times when lower hybrid waves were observed.

From 2314 to 2317 UT, three more wave bursts, spaced 1 min apart, were observed in association with fluctuations in B_Z and the total magnetic field. These three wave bursts also appear to be associated with short bursts of earthward **E**x**B** flow. Fluctuations on a ~ 1 min timescale also occurred in both electric field components and in B_X and B_Y; however, the fluctuations of B_X and B_Y were 90° out of phase with the B_Z and B_{TOTAL} fluctuations. Only the third burst of waves at 2316 UT was associated with a decrease in the local density. This burst was more intense than the two preceding wave bursts, indicating that the combination of both a density and magnetic field gradient is more favorable for wave growth. This is also consistent with the theory of the lower hybrid drift instability, since a simultaneous decrease in density and increase in the magnetic field will lower the plasma β further than just a magnetic field increase of similar magnitude.

7. Discussion

In Geotail data from five substorm onsets in the premidnight sector of the near tail studied by Sigsbee et al. (manuscript in preparation, 2000), distinct electric field and magnetic field fluctuations in the Pi2 frequency range occur right at substorm onset. These fluctuations were often compressional and were associated with magnetic field dipolarizations and earthward flow. During the November 24, 1996, substorm, compressional fluctuations in the Pi2 frequency range were observed briefly by Geotail near the onset of the expansion phase; however, the power was about an order of magnitude smaller than what was seen in the near tail by Sigsbee et al. (manuscript in preparation, 2000). Recent work has indicated a correlation between earthward flows in the near tail and Pi2 pulsations [*Shiokawa et al.*, 1998; *Kepko and Kivelson*, 1999]. Earthward flow was observed near onset at Geotail by *Petrukovich et al.* [1998] when the fluctuations in the Pi2 frequency range were observed in Geotail magnetic field data. The observations from November 24, 1996, appear to be consistent with recent work, suggesting a connection between earthward flows, compressional pulses, and Pi2 pulsations. However, it is unclear whether or not the fluctuations observed at Geotail could actually be a midtail signature of Pi2 pulsations, because so little is known about the relation between compressional pulses and earthward flows and the subsequent propagation of the compressional pulses to the ionosphere. Magnetic field fluctuations near the ion gyrofrequency were also observed during the time periods corresponding to the growth, expansion, and recovery phases of the November 24, 1996, substorm. Over the entire time period studied, the power from magnetic field fluctuations near the ion gyrofrequency was also about an order of magnitude smaller than what was seen in the near tail during substorms (Sigsbee et al., manuscript in preparation, 2000).

Analysis of the high time resolution electric field data showed that large-amplitude waves up to the lower hybrid frequency occurred during the November 24, 1996, substorm. The strongest waves were observed shortly after the onset of the expansion phase and at the start of the recovery phase.

Waves near the lower hybrid frequency during these two time periods were associated with gradients in the magnetic field and density indicated by changes in the spacecraft potential. Although the wave electric fields seen in this frequency band by Geotail during the November 24, 1996, substorm were not exceptionally large, they were similar to electric field observations in other regions of the magnetotail, with peak to peak amplitudes sometimes exceeding 20 mV/m (Sigsbee et al., manuscript in preparation, 2000). Although the electric field waveforms were sinusoidal at times, they were generally irregular and often undersampled. Large-amplitude electric field spikes, which may indicate nonlinear wave evolution, were often embedded in regions of more sinusoidal waves. The strongest peaks in the electric field power spectra in Plate 2 usually occurred at frequencies near or below the lower hybrid frequency, but power also appeared above the lower hybrid frequency, owing to these spiky electric fields. A possible explanation for these spiky electric fields is lower hybrid wave collapse. *Shapiro et al.* [1993] determined that the condition on the electric field amplitudes for the collapse of lower hybrid waves is

$$\frac{E^2}{4\pi n T_e} > \frac{m_e}{M_i}\left(\frac{\omega_{ce}}{\omega_{pe}}\right)^2 (k\rho_e)^2 \ , \qquad (1)$$

where ω_{ce} is the electron gyrofrequency, ω_{pe} is the plasma frequency, and ρ_e is the electron gyroradius. Assuming $k\,\rho_e \sim 1$, $n \sim 1$ cm^{-3}, and a temperature of 1000 eV, the electric field amplitude required by this condition for lower hybrid collapse is ~ 5 mV/m for $B \sim 5$ nT and ~ 15 mV/m for $B \sim 15$ nT. Typical electric field amplitudes observed during the November 24, 1996, substorm were from 5 to 20 mV/m, large enough to satisfy the above condition. This result agrees with *Cattell et al.* [1996], who found that the spiky electric fields observed by Geotail between 10 and 100 R_E were generally consistent with the condition for lower hybrid wave collapse for typical magnetotail parameters. The waves observed near the lower hybrid frequency during the November 24, 1996, substorm were generally larger amplitude than those observed by *Shinohara et al.* [1998] during a substorm on March 30, 1995, when Geotail was located in the near tail at a distance of 15 R_E. Shinohara et al. found that the intensity of the electric field fluctuations near the neutral sheet was much weaker than that in the outer plasma sheet. During the November 24, 1996, substorm we observed that when strong density and magnetic field gradients were present near the neutral sheet, waves with amplitudes comparable to those seen elsewhere in the plasma sheet occurred.

The behavior of the lower hybrid waves observed during the November 24, 1996, substorm basically agrees with the predictions of quasi-linear theory that this mode will be suppressed in regions with a large plasma β. However, we find that lower hybrid waves can occur even near the neutral sheet, owing to local variations in this region. The magnetic field models used to examine the theory of the lower hybrid drift instability are always simplifications of the actual physical situation, as the data in this paper show the plasma sheet can be a very turbulent region during active times. Examination of the spacecraft potential and magnetic field data in Figure 1 shows that small-scale gradients in magnetic field and density exist in the plasma sheet, in addition to the large-scale structure of this region. *Huba et al.* [1978] alluded to a mode-mode coupling process where a macroscopic MHD instability, such as a kink or tearing mode, produces local gradients in density and magnetic field that excite short-wavelength modes, such as the lower hybrid drift instability. As the data presented here have shown, variations of the electric and magnetic fields on many different spatial and temporal scales occur together in the same data set and can often be difficult to distinguish from one another. The superposition of local and large-scale variations in the plasma sheet density and magnetic field may allow the lower hybrid drift instability and other instabilities to produce small patches of turbulence throughout the magnetotail that can energize particles and provide a source of dissipation. As stated previously, B_Z is often large enough near the neutral sheet during active times so that $\beta < 1$ [*Cattell and Mozer*, 1987] . The combination of the effects of large B_Z near the neutral sheet and local variations in the plasma sheet could also allow waves to propagate.

8. Conclusions

Fluctuations of the electric and magnetic fields from 0.001 Hz up to the ion gyrofrequency and electric field fluctuations up to the lower hybrid frequency were observed by Geotail during the time periods corresponding to the growth, expansion, and recovery phases of the substorm which occurred from ~ 2050 ~ 2310 UT on November 11, 1996. The largest amplitude fluctuations over the entire frequency range considered in this paper occurred close to the onset of the expansion phase and the beginning of the recovery phase. Fluctuations of the electric and magnetic fields below 1 Hz, including fluctuations near the ion gyrofrequency and in the Pi2 frequency range, were observed during this substorm. Fluctuations below 1 Hz were typically observed during time periods when Geotail was close to the neutral sheet and the total magnetic field was ~10 nT or less. Electric and magnetic field fluctuations near and below the ion gyrofrequency have been suggested to be important to current disruption in the near tail. However, the fluctuations observed near the ion gyrofrequency in the midtail near 0100 LT during the November 24, 1996, substorm are about an order of magnitude smaller in amplitude than those observed in the premidnight sector of the near tail during substorms. Fluctuations of the electric and magnetic fields in the Pi2 frequency range were also observed in association with earthward flows. Although recent work has indicated a connection between high-speed earthward flows and the generation of Pi2 pulsations in the premidnight sector of the near tail [*Shiokawa et al.*, 1998; *Kepko and Kivelson*, 1999] , it is not certain whether the Geotail observations during the November 24, 1996, event are related to this phenomenon. Further study of magnetic field fluctuations in the Pi2 frequency range in the near tail and midtail is needed to determine the exact location where the pulsations originate at substorm onset and how they propagate through the magnetotail.

Intense waves near the lower hybrid frequency with amplitudes from a few mV/m to > 20 mV/m were observed during time periods when there were steep gradients in the magnetic field and density, as indicated by the spacecraft potential. During the recovery phase, waves near the lower hybrid frequency appeared to be suppressed at the neutral sheet when the total magnetic field was close to zero, in agreement with predictions of quasi-linear theory. However, wave activity near and below the lower hybrid frequency was reinitiated as soon as the *Z* component of the magnetic field increased by a few nanoteslas. Although the observations presented in this paper cannot resolve the controversy surrounding the microphysical processes that occur in the plasma sheet during substorms, they clearly show that large-amplitude waves near the lower hybrid frequency occur during the substorm expansion and recovery phases. Because Geotail was not located in the region where the near-Earth neutral line usually forms, the lower hybrid waves observed during this substorm were probably not involved in magnetic reconnection. However, the observed waves still could provide a significant source of ion heating and energization. A detailed study of the occurrence of lower hybrid waves in the magnetotail is needed in order to understand if these waves actually do provide a source of heating and energization of particles throughout the magnetotail, and what effect this has on the dynamical processes that occur in the magnetotail during substorms.

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References

Cattell, C. A., and F. S. Mozer, Substorm electric fields in the Earth's magnetotail, in *Magnetic Reconnection in Space and Laboratory Plasmas, Geophys. Monogr. Ser.*, vol. 30, edited by E. W. Hones Jr., pp. 208-215, AGU, Washington, D. C., 1984.

Cattell, C. A., and F. S. Mozer, Substorm-associated lower hybrid waves in the plasma sheet observed by ISEE 1, in *Magnetotail Physics,* edited by A. T. Y. Lui, pp. 119-125, Johns Hopkins Univ. Press, Baltimore, Md., 1987.

Cattell, C. A., M. Kim, R. P. Lin, and F. S. Mozer, Observations of large electric fields near the plasma sheet boundary by ISEE-1, *Geophys. Res. Lett., 9,* 539-542, 1982.

Cattell, C., F. Mozer, K. Tsuruda, H. Hayakawa, M. Nakamura, T. Okada, S. Kokubun, and T. Yamamoto, Geotail observations of spiky electric fields and low-frequency waves in the plasma sheet and plasma sheet boundary, *Geophys. Res. Lett., 21,* 2987-2990, 1994.

Cattell, C. A., I. Roth, and M. Linton, The effects of low frequency waves on ion trajectories in the Earth's magnetotail, *Geophys. Res. Lett., 22,* 3445-3448, 1995.

Cattell, C., T. Bennett, K. Sigsbee, T. Streed, F. S. Mozer, I. Roth, K. Tsuruda, T. Yamamoto, T. Okada, and S. Kokubun, Effects of low frequency waves and spiky electric fields in the magnetotail, in *Proceedings of the Third International Conference on Substorms,* edited by E. J. Rolfe and B. Kaldeich, pp. 521-526, Eur. Space Agency, Noordwijk, The Netherlands, 1996.

Huba, J. D., N. T. Gladd, and K. Papadopoulos, The lower-hybrid-drift instability as a source of anomalous resistivity for magnetic field line reconnection, *Geophys. Res. Lett., 4,* 125, 1977.

Huba, J. D., N. T. Gladd, and K. Papadopoulous, Lower-hybrid-drift wave turbulence in the distant magnetotail, *J. Geophys. Res., 83,* 5217-5225, 1978.

Jacquey, C., J. A. Sauvaud, D. Popescu, H. Rème, D. G. Sibeck, S. I. Klimov, S. A. Romanov, R. P. Lepping, and G. D. Reeves, Large scale response of the magnetotail to a substorm expansion: Interball and IMP-8 observations on November 24, 1996, in *Substorms-4,* edited by S. Kokubun and Y. Kamide, pp. 155-158, Kluwer Acad., Norwell, Mass., 1998.

Kepko, L., and M. Kivelson, Generation of Pi2 pulsations and bursty bulk flows, *J. Geophys. Res., 104,* 25,021-25,034, 1999.

Kokubun, S., T. Yamamoto, M. H. Acuña, K. Hayashi, K. Shiokawa, and H. Kawano, The Geotail magnetic field experiment, *J. Geomagn. Geoelectr., 46,* 7-21, 1994.

Kumar, P., and E. Foufoula-Georgiou, Wavelet analysis in geophysics: An introduction, in *Wavelets in Geophysics,* edited by E. Foufoula-Georgiou and P. Kumar, pp. 1-43, Academic, San Diego, Calif., 1994.

Lui, A. T. Y., Current disruption in the Earth's magnetosphere: Observations and models, *J. Geophys. Res., 101,* 13,067-13,088, 1996.

Lui, A. T. Y., R. E. Lopez, B. J. Anderson, K. Takahashi, L. J. Zanetti, R. W. McEntire, T. A. Potemra, D. M. Klumpar, E. M. Greene, and R. Strangeway, Current disruptions in the near-Earth neutral sheet region, *J. Geophys. Res., 97,* 1461-1480, 1992.

Machida, S., Y. Miyashita, A. Ieda, A. Nishida, T. Mukai, Y. Saito, and S. Kokubun, Geotail observations of flow velocity and north-south magnetic field variations in the near and mid-distant tail associated with substorm onsets, *Geophys. Res. Lett., 26,* 635-638, 1999.

Nagai, T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T. Yamamoto, T. Mukai, A. Nishida, and S. Kokubun, Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations, *J. Geophys. Res., 103,* 4419-4440, 1998.

Okada, T., et al., Geotail observations of electrostatic waves near the lower hybrid frequency range in the plasma sheet boundary layer, *Geophys. Res. Lett., 21,* 2931-2934, 1994.

Pedersen, A., Solar wind and magnetosphere plasma diagnostics by spacecraft electrostatic potential measurements, *Ann. Geophys., 13,* 118-129, 1995.

Petrukovich, A. A., S. A. Romanov, L. M. Zelenyi, T. Mukai, Y. Saito, T. Yamamoto, S. Kokubun, and O. A. Troshichev, Substorm-associated pressure variations in the magnetotail, in *Substorms-4,* edited by S. Kokubun and Y. Kamide, pp. 199-202, Kluwer Acad., Norwell, Mass., 1998.

Rioul, O., and P. Flandrin, Time-scale energy distributions: A general class extending wavelet transforms, *IEEE Trans. Signal Proc., 40,* 1746-1757, 1992.

Samson, J. C., and J. V. Olson, Some comments on the description of the polarization states of waves, *Geophys. J. R. Astron. Soc., 61,* 115-129, 1980.

Shapiro, V. D., V. Shevchenko, G. Solov'ev, V. Kalinin, R. Bingham, R. Sagdeev, M. Ashour-Abdalla, J. Dawson, and J. Su, Wave collapse at the lower hybrid resonance, *Phys. Fluids B, 5,* 3148-3162, 1993.

Shinohara, I., T. Nagai, M. Fujimoto, T. Terasawa, T. Mukai, K. Tsuruda, and T. Yamamoto, Low-frequency electromagnetic turbulence observed near the substorm onset site, *J. Geophys. Res., 103,* 20,365-20,388, 1998.

Shiokawa, K., et al., High-speed ion flow, substorm current wedge, and multiple Pi 2 pulsations, *J. Geophys. Res., 103,* 4491-4508, 1998.

Tsuruda, K., H. Hayakawa, M. Nakamura, T. Okada, A. Matsuoka, F. S. Mozer, and R. Schmidt, Electric field measurement on the Geotail satellite, *J. Geomagn. Geoelectr., 46,* 693-711, 1994.

Yumoto, K., K. Takahashi, T. Saito, F. W. Menk, B. J. Fraser, T. A. Potemra, and L. J. Zanetti, Some aspects of the relation between Pi 1-2 magnetic pulsations observed at L=1.3-2.1 on the ground and substorm-associated magnetic field variations in the near-Earth magnetotail observed by AMPTE CCE, *J. Geophys. Res., 94,* 3611-3618, 1989.

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