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30. Broadband Plasma Waves in the Magnetopause and Plasma-Sheet Boundary Layers

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1. ABSTRACT

The magnetopause and plasma-sheet boundary layers can support a wide spectrum of plasma waves, from a few mHz to several 100 kHz. The main characteristic features of the broadband plasma waves, which have been observed in these boundary layers by several spacecraft, and their possible generation mechanism are described. High-time-resolution-waveform observations by the plasma-wave instrument onboard the Geotail, Polar, and FAST spacecraft have shown that broadband plasma waves (at least, the higher frequencies) consist of a series of bipolar solitary pulses. However, the low-frequency part of the broadband wave spectrum is not well understood. The broadband plasma waves can play an important role in the heating and acceleration of the charged particles on the auroral field lines. As an example, it is shown that the cyclotron resonant interaction of energetic particles with the waves can lead to their rapid pitch-angle scattering. The resulting precipitated energy flux to the ionosphere may be sufficient to create the diffuse auroral oval.

2. INTRODUCTION

The magnetopause boundary layer is the region where solar-wind energy and momentum is transferred into the magnetosphere. Solar-wind plasma can cross the magnetopause and enter the magnetosphere, either by a direct entry involving magnetic reconnection, or by the cross-field transport due to the scattering of particles by the waves across closed magnetopause field lines [*Tsurutani and Thorne, 1982*; *Baumjohann and Paschmann, 1987*; *Lee et al., 1994*]. The reconnection process is more likely to be important when the interplanetary magnetic field (IMF) is directed southward, whereas the wave-particle transport may dominate during the northward IMF intervals [*Tsurutani and Gonzalez, 1995*]. The boundary layers (BLs) occurring in space plasmas can support a wide spectrum of waves, depending upon their plasma and field properties. In the magnetopause boundary layer, plasma waves with frequencies less than 1 Hz to 100 kHz and higher have been observed. These broadband boundary-layer waves can play an important role in the cross-field transport processes. These waves can diffuse the magnetosheath plasma across the closed magnetospheric field lines at a rate rapid enough to create the low-latitude boundary layer (LLBL) itself [*Tsurutani and Thorne, 1982*; *Gendrin, 1979, 1983*; *Thorne and Tsurutani, 1991*]. Thus, the cross-field transport due to these waves could provide a specific mechanism for "viscous interaction" [*Axford and Hines, 1961*, *Eviatar and Wolf, 1968*; *Tsurutani and Gonzalez, 1995*], which helps to transfer solar-wind flow energy to the magnetosphere. The cyclotron resonant interaction of the low-latitude boundary layer waves and the energetic particles can put protons and electrons on near-strong to strong pitch-angle diffusion to create the dayside aurora at the Earth [*Tsurutani et al., 1981*], a phenomena that is ever-present and is independent of substorms. Furthermore, the magnetopause boundary-layer waves may give rise to enough dissipation, and, thus, act as a trigger for magnetic reconnection to occur [*Cattell et al., 1995*].

The broadband electrostatic noise (BEN) has been observed in the neutral sheet by IMP-7 [*Scarf et al., 1974*], and in the plasma-sheet boundary layer (PSBL) by IMP-8 [*Gurnett et al., 1976*]. These broadband plasma waves have been suggested as the source of hot ions in the central plasma sheet (CPS) [*Eastman et al., 1984*]. Geotail observations indicate that the broadband noise consists of short-duration pulses of solitary waves [*Matsumoto et al., 1994*].

Recent analysis of Polar plasma-wave data [*Tsurutani et al., 1998a*] have indicated that broadband waves, with properties similar to those at the magnetopause boundary layer, exist on field lines bounding the polar cap (thus they are called Polar-Cap Boundary-Layer waves). It is speculated that these waves are on low-latitude boundary-layer magnetic field lines, but at lower altitudes, *Lakhina et al.* [*2000a*] and *Lakhina and Tsurutani* [*1999a*] have summarized the properties of broadband plasma waves in various boundary layers. Here, we shall review the characteristics of high-frequency (wave frequency $f > 1\,\mathrm{Hz}$) broadband plasma waves, observed in the magnetopause boundary and in the plasma-sheet boundary layer. In both of these regions, the low-frequency component of these waves could play a crucial role in the heating, acceleration, and cross-field diffusion of the electrons and ions.

Sections 2 and 3 give description of the broadband plasma waves observed in the magnetopause and plasma-sheet boundary layers in the frequency domain. This is the traditional approach, based on the wave modes and relevant instabilities, and it has proven useful in understanding the fundamental characteristics of plasma waves, as well as in the determination of the wave modes. Section 4 describes some of the important plasma-instability mechanisms that have been put forward for the generation of broadband plasma waves. Section 5 describes the latest results on the broadband plasma waves coming out from the time-domain studies. The summary of the results and the conclusions are given in Section 6.

3. MAGNETOPAUSE BOUNDARY-LAYER WAVES

The Earth's magnetopause represents a complex, variable boundary. Spacecraft observations have shown that the magnetopause boundary layer is the site of ultra-low-frequency (ULF) and extremely-low-frequency (ELF) waves [*Anderson, 1995*]. These low-frequency waves are probably generated either by the magnetopause boundary motions, or by the Kelvin-Helmholtz instabilities, tearing instabilities, or by drift-wave-type instabilities [*Holzer et al., 1966; Miura, 1987*; *Sckopke et al., 1981*; *Lakhina et al., 1993*; *Anderson, 1995*; *Lakhina and Schindler, 1996*]. From the HEOS-2 magnetic data, *Bahnsen* [*1978*] showed that the wave amplitudes, in the frequency range 20-235 Hz, peaked at the magnetopause, and that the power spectral density fell off with increasing frequency.

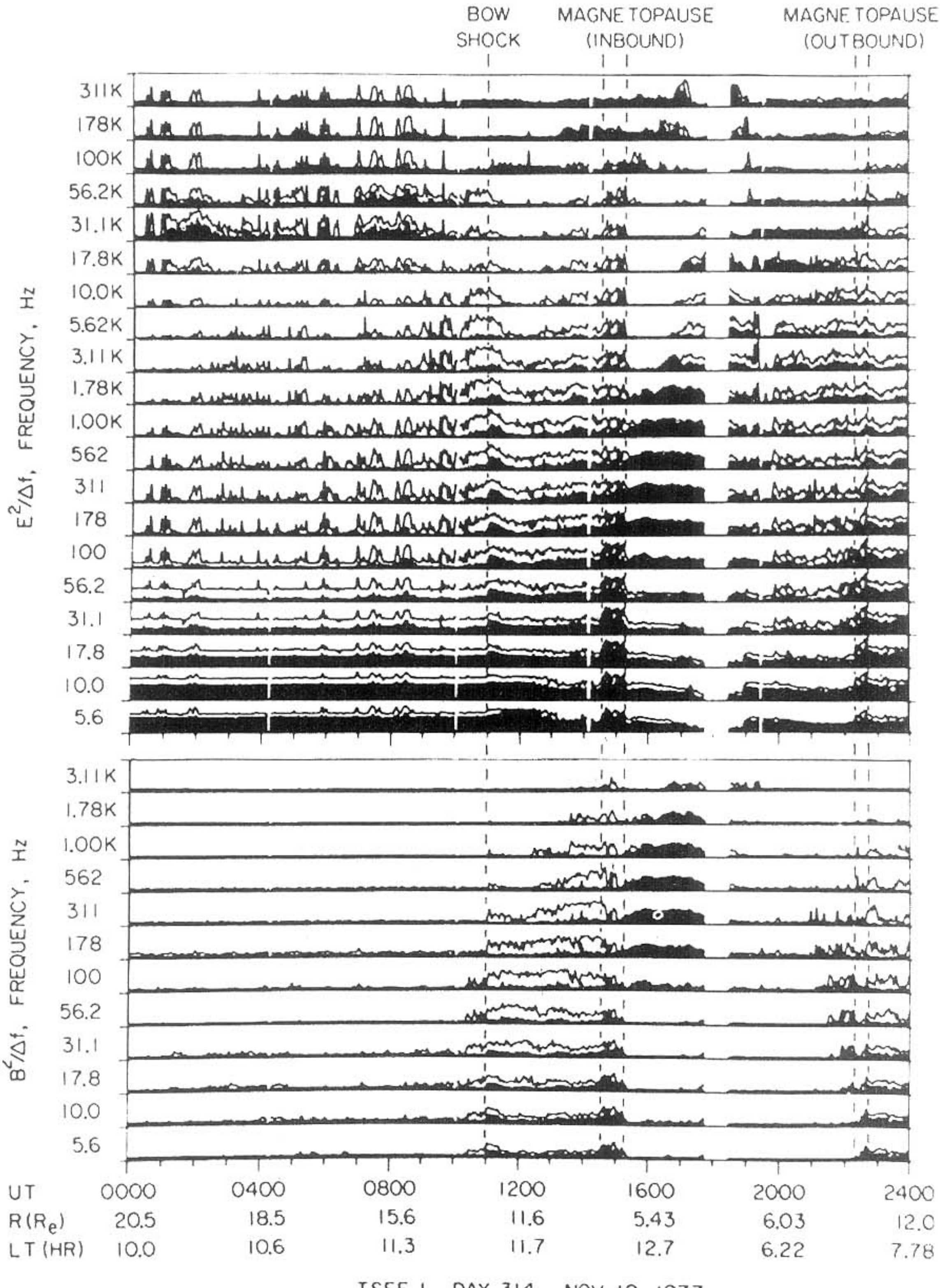

Figure 1. The plasma-wave electric and magnetic field data from ISEE 1 for a representative pass through the magnetosphere. The enhanced electric and magnetic field intensities at the inbound and outbound magnetopause crossings are clearly indicated (from *Gurnett et al.* [*1979*], Figure 1).

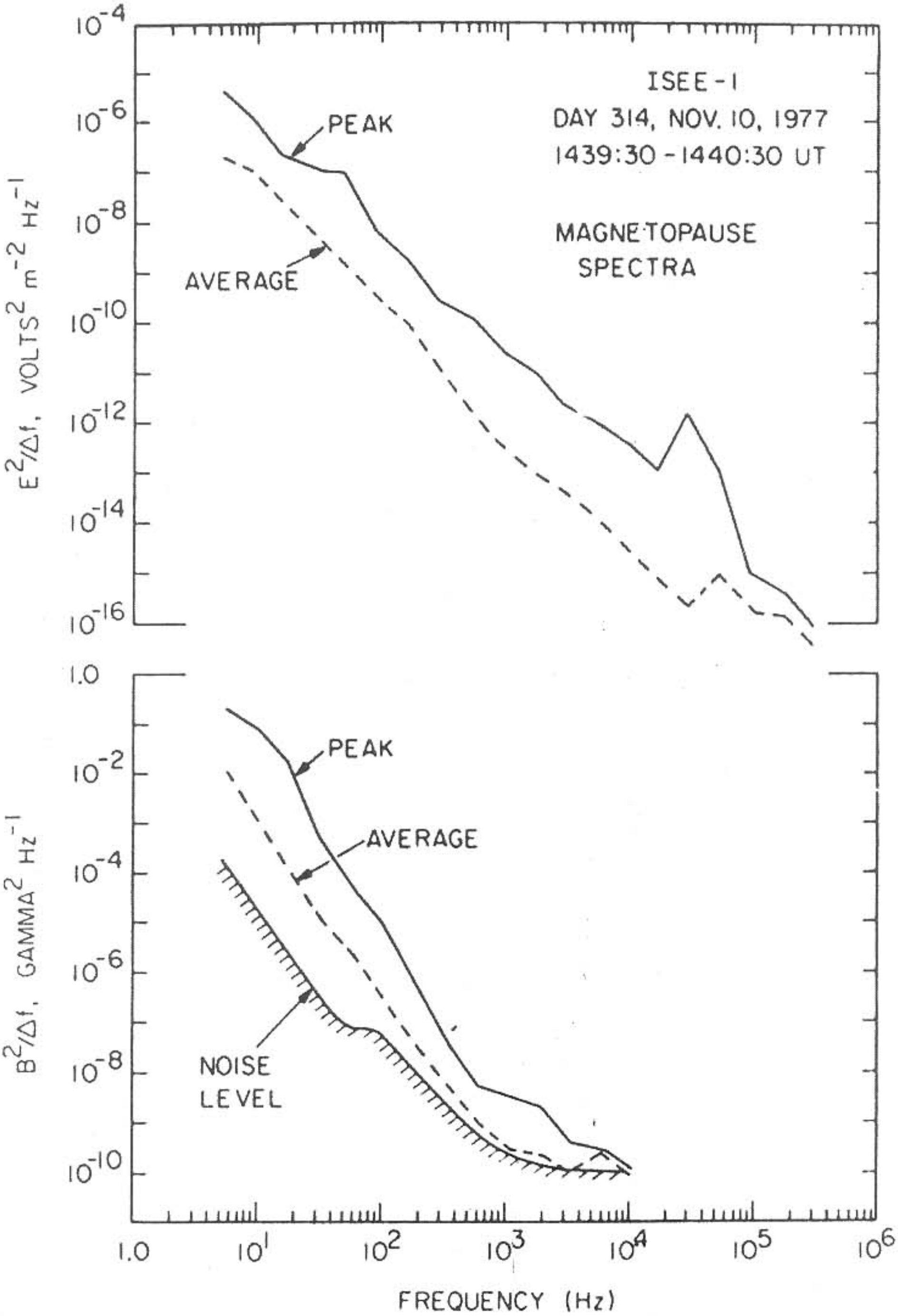

Figure 2. These plots show the typical electric and magnetic field spectra of the enhanced plasma-wave turbulence observed near the magnetopause (from *Gurnett et al.* [*1979*], Figure 10).

Gurnett et al. [*1979*] were the first to report the results on both the plasma-wave electric and magnetic fields in the vicinity of the magnetopause, using measurements from the ISEE 1 and 2 spacecraft. They found that the maximum plasma-wave intensities usually occurred at the magnetopause. An example is shown in Figure 1. They observed magnetic waves in the frequency range extending from below 5.6 Hz to 1 kHz, characterized by an $f^{-3.3}$ power-law spectrum. The electric-field turbulence occurred in the frequency range extending from below 5.6 Hz to 100 kHz, and had a featureless spectrum obeying an $f^{-2.2}$ power law, as shown in Figure 2. In a few cases, *Gurnett et al.* [*1979*] could determine that the wave electric field had perpendicular polarization. *Gurnett et al.* [*1979*] suggested that the magnetic waves are whistler modes, and that the electric component is a superposition of some electrostatic emissions and the electric component of the whistler mode. *Tsurutani et al.* [*1981*] studied 10 ISEE 1 and 2 magnetopause crossings, and found an average magnetic wave spectrum to be $10f^{-3.9}\ \mathrm{nT^2\,Hz^{-1}}$ for the frequency range of (10-1000) Hz. A typical electric-wave spectrum in the frequency range (10 - 10^5) Hz was characterized by $3\times10^{-5} f^{-2.8}\ \mathrm{V^2m^{-2}Hz^{-1}}$. However, both the magnetic and electric wave spectra varied by an order of magnitude in amplitude from case to case. *Anderson et al.* [*1982*] found that the plasma-wave characteristics of the flux-transfer events (FTEs), magnetopause current layer, and the boundary layer were nearly identical.

The wave intensity of the boundary-layer magnetic-wave spectrum at frequencies below 11 Hz, observed by GEOS-2, was found to decrease monotonically with increasing frequency [*Gendrin, 1983*]. *Rezeau et al.* [*1986*] showed that the magnetopause boundary-layer spectrum is enhanced above the magnetosheath spectrum (above 1 Hz), and has a similar frequency dependence. Recently, *Rezeau et al.* [*1999*] showed that the magnetic fluctuations at the magnetopause exhibit power-law spectra up to the lower-hybrid frequency.

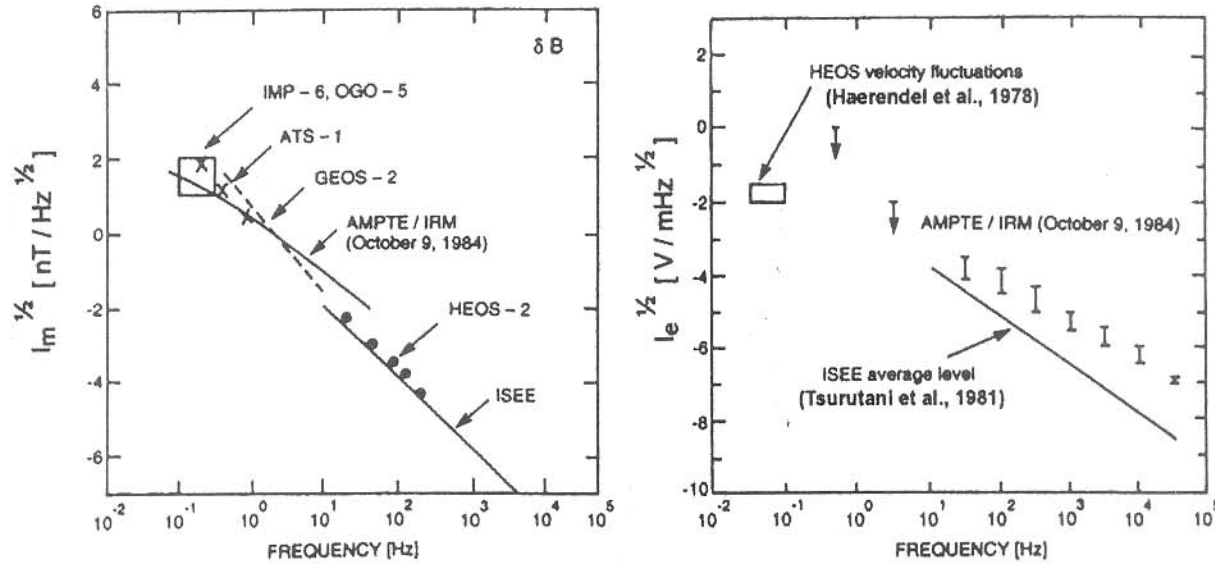

Figure 3. (left) The spectrum of magnetic fluctuations observed at the magnetopause from various different satellites. (right) The spectrum of electric fluctuations observed at the magnetopause from ISEE and from AMPTE/IRM. The IRM data come from a single day; the maximum value at the magnetopause is shown, along with the spectrum averaged over the magnetopause region. The IRM data from below 30 Hz are only upper limits on the wave amplitude. Also shown is the typical value of electric-field fluctuations below 0.1 Hz, corresponding to the velocity fluctuations reported from the HEOS satellite (from *LaBelle and Treumann* [*1988*], Figures 2 and 3).

LaBelle and Treumann [*1988*] analyzed the AMPTE/IRM plasma-wave data and found that the spectrum of electric as well as magnetic fluctuations decreases with frequency, as found by *Gendrin* [*1983*] and *Rezeau et al.* [*1986*]. A comparison of many spacecraft observations for the magnetopause boundary-layer waves, as summarized by *LaBelle and Treumann* [*1988*], is shown in Figure 3. It can be seen that nearly all measurements generally fit power-law spectra for both electric and magnetic components. The various measurements all agree with one another within an order of magnitude in power, which is the typical variation of the spectra from one event to another, as found by *Tsurutani et al.* [*1981*].

Tsurutani et al. [*1989*] performed a statistical study of the broadband plasma waves at the magnetopause, and showed that the correlation of the wave electric component with parameters such as local time, latitude, magnetosheath field strength, and on magnetopause position was quite weak. Although wave amplitudes were highly variable from event to event, the wave spectra averaged over many passes are remarkably similar at dawn, noon, and dusk local hours, as seen from Figures 4 and 5. The waves were found to be more intense during negative magnetosheath (interplanetary) B_z than during positive B_z. *Zhu et al.* [*1996*] find a nearly linear relationship between the local magnetic-shear angle and the wave amplitudes (both electric and magnetic components). Recently, *Song et al.* [*1998*] found a clear correlation between the broadband waves and the electron-plasma beta, but no clear correlation between the wave amplitudes and the electron anisotropy.

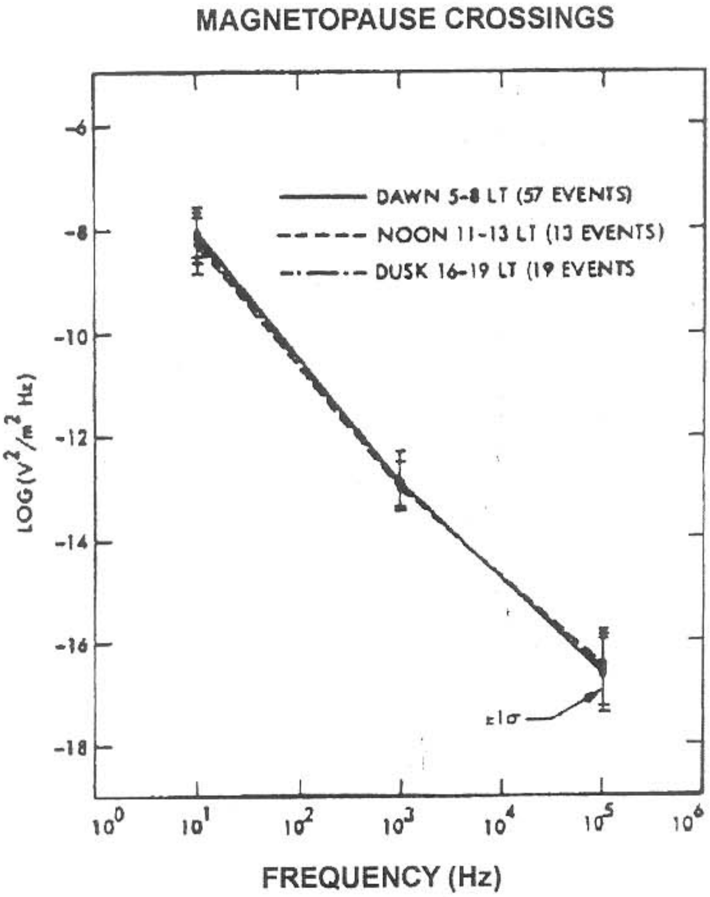

Figure 4. The average wave three-point electric field spectra (at 10^1, 10^3, and 10^5 Hz), for three different local times (dawn, noon, and dusk). Fifty-seven events near dawn (0500-0800 LT), 13 events near noon (1100-1200 LT), and 19 events near dusk (1600-1900) were each grouped together for this study. The average spectra are remarkably similar to each other in both shape and intensity (from *Tsurutani et al.* [*1989*], Figure 6).

Recently, from the analysis of the plasma-wave data from the Polar spacecraft, *Tsurutani et al.* [*1998a*] reported the presence of intense broadband plasma waves on the polar-cap magnetic field lines, which map to the low-latitude boundary layer. These waves are spiky, and their frequency dependences and intensities are quite similar to those of the low-latitude boundary layer

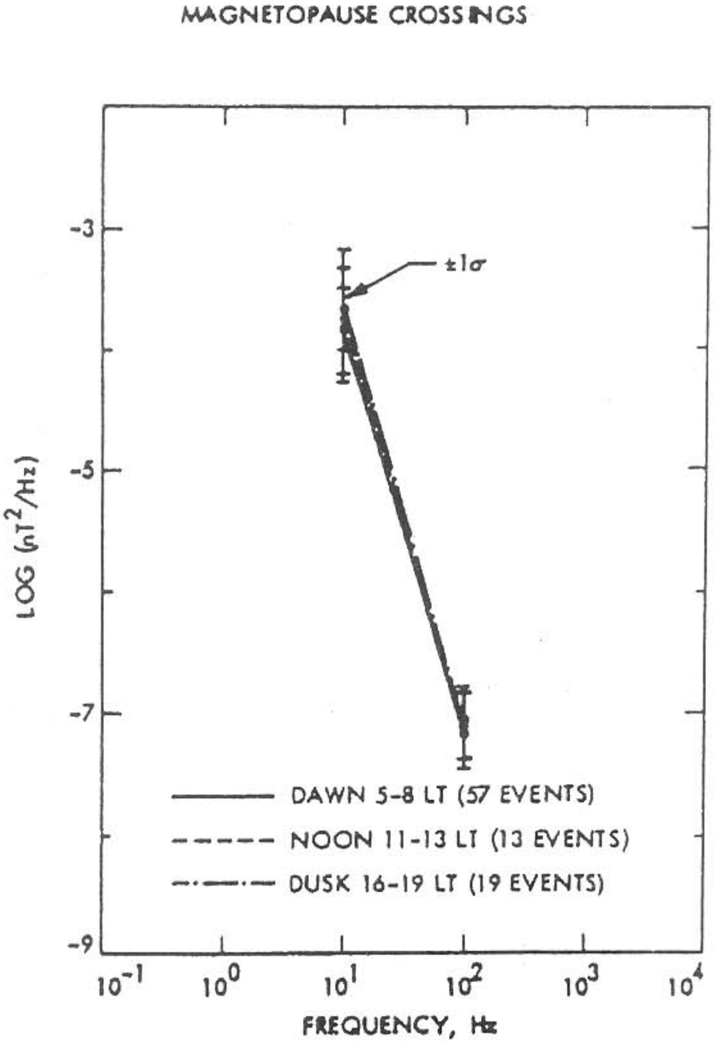

Figure 5. The same as in Figure 4, except for the wave magnetic component (from *Tsurutani et al.* [*1989*], Figure 7).

(LLBL) waves, detected at and inside the low-latitude dayside magnetopause. These waves, therefore, are called polar-cap boundary-layer (PCBL) waves. Figure 6 shows the Polar orbit, which has an inclination of 86° with an apogee of $\sim 9\,R_E$ and a perigee of $\sim 1.8\,R_E$, and covers the noon-midnight sector. Under ordinary circumstances, the Polar spacecraft does not intercept the magnetopause, but as shown in the figure, the spacecraft does cross field lines that map into the low-latitude boundary layer.

In the Polar study, the spectral-density plots for both electric and magnetic field were found to have rough power-law shapes, even though the intensities and spectral shapes vary from event-to-event. The electric and magnetic spectra of a typical event, which occurred near the apogee in the northern hemisphere on Day 98, 1996, at 1302 MLT at 78.8° N invariant magnetic latitude, is shown in Figure 7. Note that the electric component of the waves extends to frequencies above the electron-cyclotron frequency. Figure 8 shows the schematics of the magnetic field, regions of PCBL wave detection, and low-latitude boundary-layer wave locations. It is most probable that waves are present all along the boundary-layer field lines.

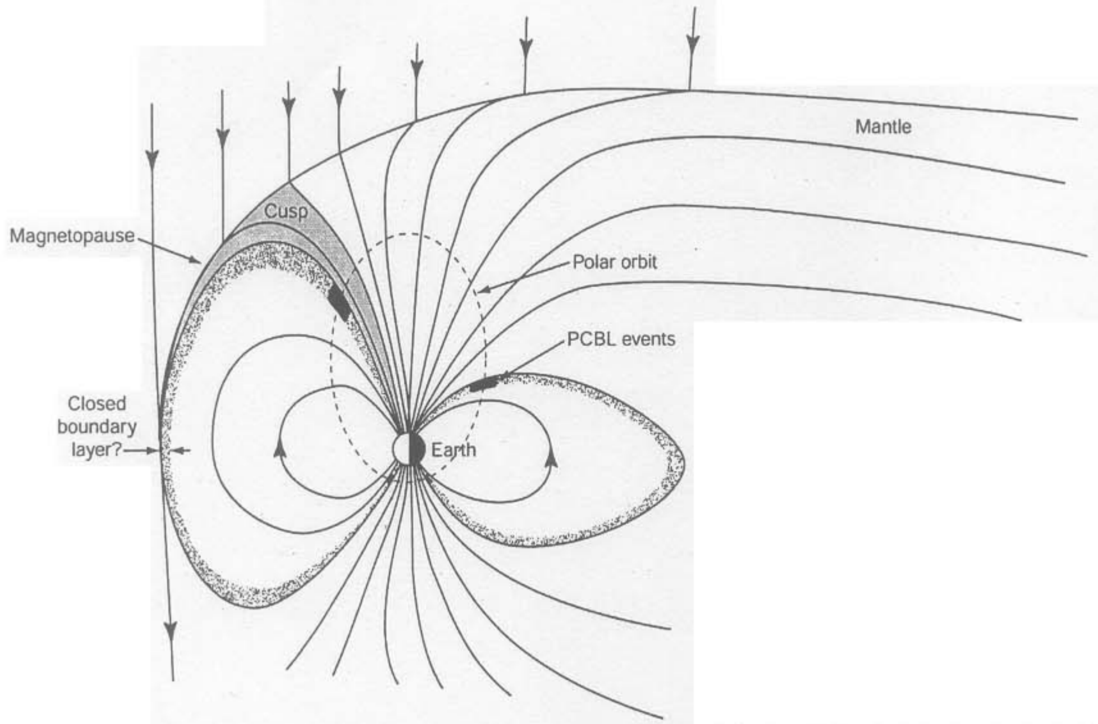

Figure 6. The Polar orbit and the region of wave detection (solid bar) in the magnetosphere. Polar has a perigee at $1.8 R_E$ and an apogee at $9 R_E$. Waves on the field lines that map into the low-latitude boundary layer (LLBL) are the topic of this study (from *Tsurutani et al.* [*1998a*], Figure 1).

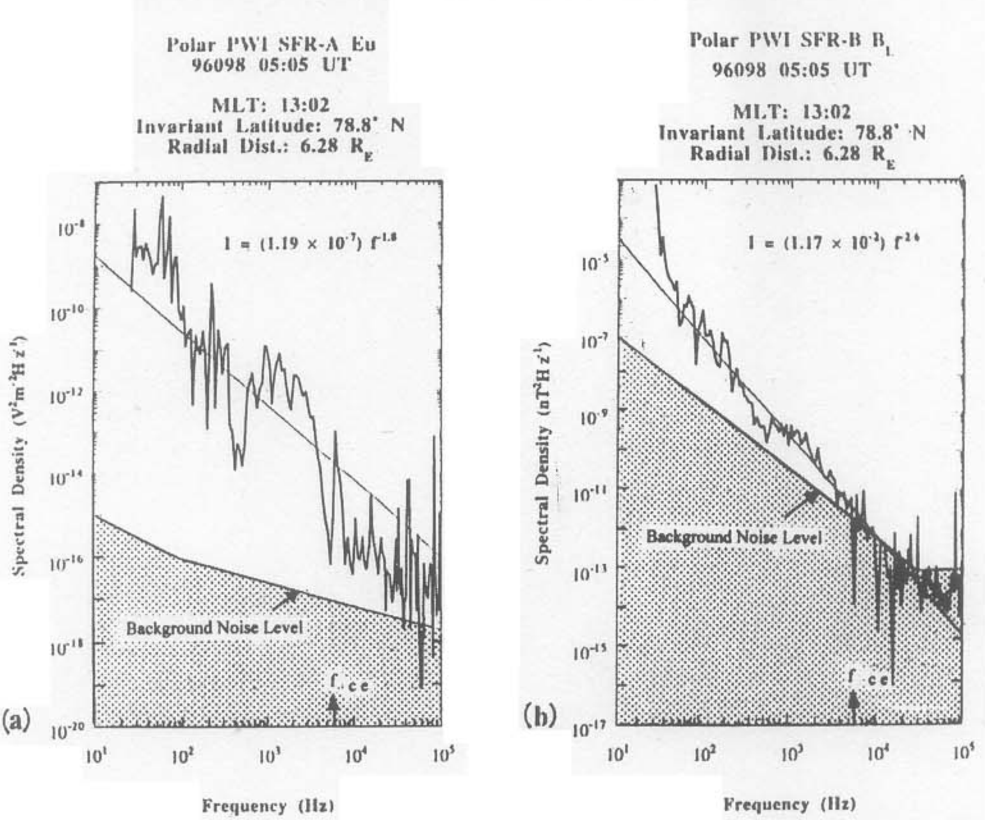

Figure 7. The electric-field (a) and magnetic-field (b) spectra for the events occurring on Day 098, 1996. The background noise is indicated. The electric component of the waves extends beyond the electron-cyclotron frequency ($\sim 6 \times 10^3$ Hz) (from *Tsurutani et al.* [*1998a*], Figure 5).

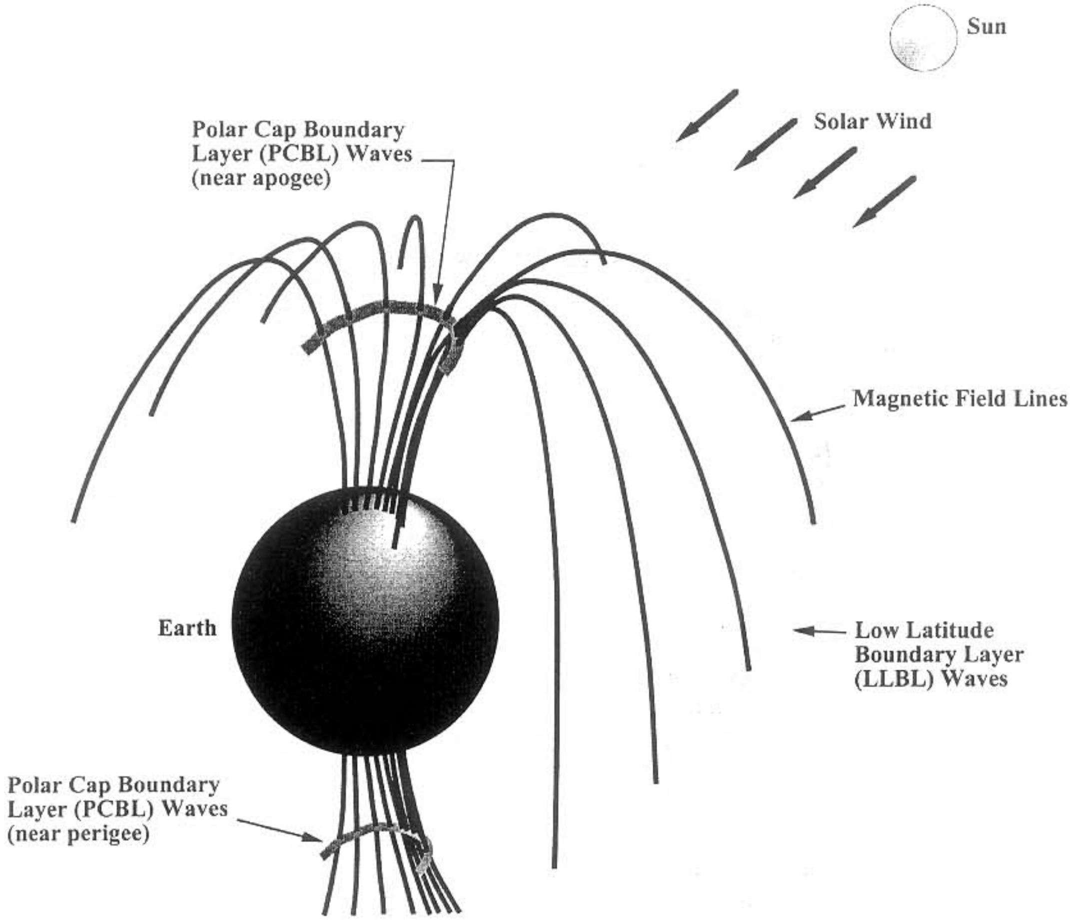

Figure 8. A schematic of the Earth's magnetic-field-line mapping through regions of polar-cap boundary-layer (PCBL) waves and low-latitude boundary-layer (LLBL) waves (from *Tsurutani et al.* [*1998a*], Figure 8).

4. PLASMA-SHEET BOUNDARY-LAYER WAVES

Broadband electrostatic emissions were observed around the plasma-sheet boundary layer by *Gurnett et al.* [*1976*]. They referred to these emissions as "broadband electrostatic noise (BEN)." They reported the BEN's detailed features using the plasma-wave data from IMP-8, which passes through the magnetotail at radial distances ranging from about $23 R_E$ to $46 R_E$. Figure 9 shows a typical spectrum of broadband electrostatic noise, observed by IMP-8. BEN usually occurs over a broad range of frequencies, extending from about 10 Hz to a few kHz, with intensities ranging from about 50 μV/m to 5 mV/m. The spectrum of BEN consists of many discrete bursts, lasting from a few seconds to several minutes (cf. Figure 6 of *Gurnett et al., 1976*). The spectrum shows a marked decrease in intensity at the electron-cyclotron frequency, and a lower cutoff at the local lower-hybrid resonance frequency. For Figure 9, the electron-cyclotron frequency was approximately 300 Hz, and the lower-hybrid frequency was approximately 7 Hz. The wave electric field was found to be oriented within ±20° from perpendicular to the magnetic field. BEN is commonly observed in the plasma-sheet boundary layer, with a strong correlation with high-energy ion flows. This correlation has lead to many possible theoretical mechanisms for BEN generation in terms of ion-beam instabilities [*Grabbe, 1985*]. *Tsutsui et al.* [*1991*] attempted to explain the broad frequency characteristics of BEN by the Doppler-shifted ion-acoustic potential bubbles convecting with the plasma bulk flow, which was taken equal to the ion flow.

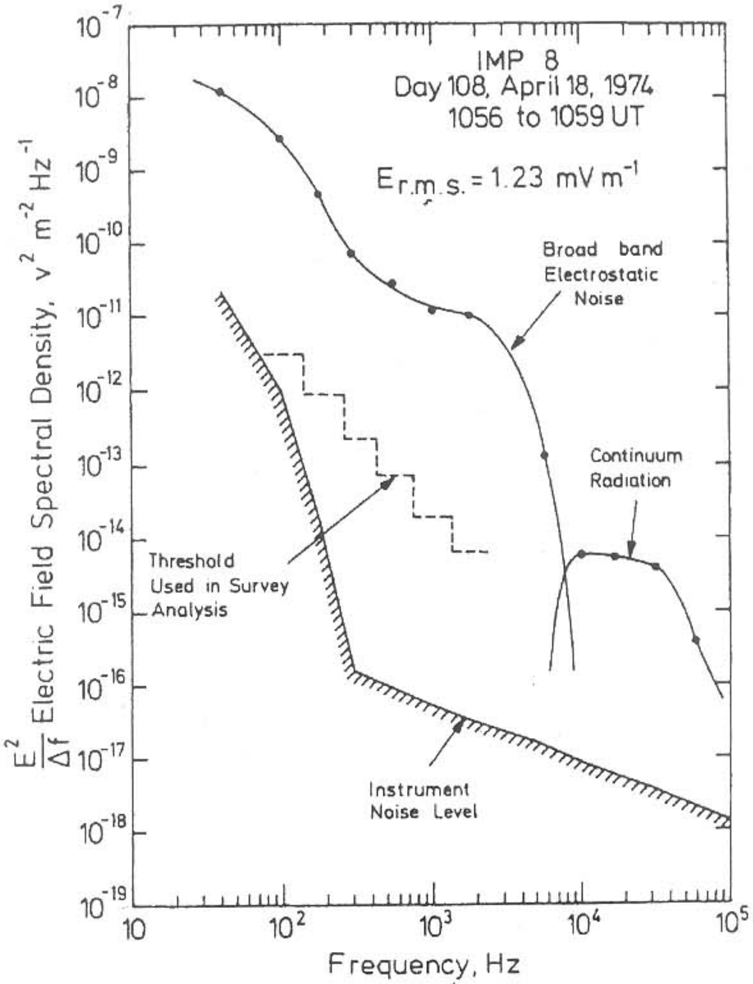

Figure 9. A typical frequency spectrum of the broadband electrostatic noise observed by the IMP 8 spacecraft (taken from Figure 5 in [*Gurnett et al., 1976*]).

On the other hand, *Parks et al.* [*1984*] demonstrated the relation of the BEN and electron beams, based on the observations by the ISEE-1 spacecraft. *Onsager et al.* [*1993*] showed that BEN can be observed in the electron layer of the outer PSBL without energetic ions. They pointed out that the ion streaming is not essential for the excitation of BEN, and stressed that BEN has a close relationship to the electron dynamics. Further, the analysis of *Onsager et al.* [*1993*] indicated the high-frequency part of BEN spectra to be polarized parallel to the magnetic field. *Nishida et al.* [*1985*] suggested that the high-frequency part of BEN is not a normal mode: rather, it may correspond to potential structures picked up very close to electric-field antennas.

5. GENERATION MECHANISMS

The plasma waves observed in the magnetopause and plasma-sheet boundary are broadband, with no prominent spectral peaks that could be used to identify the plasma instabilities exciting these modes. As the boundary layers are the site of many free-energy sources existing simultaneously, it is not an easy task to identify which free-energy source could be dominant for a given event. The changing interplanetary conditions can further complicate the identification of the free-energy source and relevant plasma instability driven by it. The gradients in density, temperature, velocity, and magnetic field, sometimes all together, are present at the boundary layers. These gradients could act as sources of free energy for wave generation. In addition, the boundary layers can support strong currents, particle beams, and anisotropic velocity-space distributions, which, again, can drive many plasma instabilities. *Lakhina et al.* [*2000a*, *2000b*] have described several possible generation mechanisms for the broadband boundary-layer waves. We shall discuss some of them briefly here.

The lower-hybrid drift instability (LHDI), driven essentially by the density gradients, has been studied extensively to explain the broadband waves observed at the magnetopause [*Gary and Eastman, 1979*; *Huba et al., 1981*; *Revathy and Lakhina, 1977*; *Gary and Sgro, 1990*; *Winske and Omidi, 1995*; *Winske et al., 1995*]. It is basically an electrostatic instability, and the waves are generated near the lower-hybrid wave frequencies. Some other popular wave-generation mechanisms are based on field-aligned current-driven instabilities, like the ion-acoustic instability [*Kindel and Kennel, 1971*], the ion-cyclotron instability [*Ashour-Abdalla and Thorne, 1978*], ion-beam instabilities (*Verheest and Lakhina, 1991, 1993; Lakhina, 1993*; *Grabbe and Eastman, 1984*; *Grabbe, 1985*; *Dusenbury and Lyons, 1985*; *Akimoto and Omidi, 1986*; *Ashour-Abdalla and Okuda, 1986*], electron-beam instabilities (*Schriver and Ashour-Abdalla, 1989*; *Parks et al., 1984*; *Onsager et al., 1983*; *Baumjohann et al., 1989*; *Matsumoto et al., 1994*; *Omura et al., 1996*], loss-cone instabilities generated by the electron-loss distributions [*Kennel and Petschek, 1966*], and velocity-shear and current-convective instabilities [*D'Angelo, 1977*; *Miura, 1987*; *Lakhina, 1987, 1994*; *Ganguli et al., 1994*; *Drake et al., 1994a, 1994b*; *Drake, 1995*; *Zhu et al., 1996*]. The mechanism of the current-convective instability demands the thickness of the magnetopause current layer, *L*, to be very narrow, such that $L < \delta_e$, where $\delta_e = c/\omega_{pe}$ (c and ω_{pe} are the speed of light and the electron plasma frequency, respectively) is the electron skin depth. The whistler instability, on the other hand, requires that $L < \delta_i$, where $\delta_i = c/\omega_{pi}$ is the ion skin depth. The observed thickness of the magnetopause is typically several times the ion skin depth. Although all these mechanisms can explain the strongest wave power at the lowest frequencies, they suffer from a common drawback as to how to cascade the power up to VLF frequencies.

Lakhina and Tsurutani [*1999b*] have presented a linear theory for the generation of broadband polar-cap boundary-layer plasma waves. Their Coupled Velocity Shear-Lower Hybrid Instabilities Model is based on two-fluid equations, is fully electromagnetic, and takes into account the free energy available due to the presence of field-aligned currents, and gradients in the currents, the plasma densities, and the magnetic fields. The dispersion relation generalizes the dispersion relations for several plasma modes, including the lower-hybrid [*Gary and Eastman, 1979*], the modified two-stream instability [*Lakhina and Sen, 1973*], beam modes [*Dum, 1989*; *Lakhina, 1993*], current-convective, and whistler instabilities [*Drake et al., 1994a*; *Drake, 1995*]. In general, the beam-driven modes, the current-convective and the lower-hybrid drift modes are coupled, and the dispersion relation has to be solved numerically. It is found that density gradients tend to stabilize both the current-convective and the whistler instabilities at the same time these modes develop real frequencies. On the other hand, sharp density gradients can lead to the excitation of a lower-hybrid drift instability when the hot ions are present in the boundary layer.

5.1 Cross-Field Diffusion

The magnetopause as well as the plasma-sheet boundary layer is essentially a collisionless plasma system. However, the interaction of broadband plasma waves with the charged particles can cause scattering of the particles, thereby changing particles' momenta and energies. Therefore, wave-particle interactions in a collisionless boundary-layer plasma can play a role similar to direct particle-particle collisions in a collisional plasma. In the absence of particle scattering of the waves, the magnetosheath ions are expected to penetrate the magnetopause boundary to a maximum distance of the order of a Larmor radius, when the charge-separation electric field is completely neutralized by the ionospheric plasma. Since the magnetopause thickness is generally much greater than an ion Larmor radius, the particle cross-field transport, due to the wave-particle interaction, has been invoked to explain the formation of the boundary layer.

A particle can interact strongly with the waves when it senses the wave Doppler-shifted to its cyclotron frequency (or its harmonics). This process is known as cyclotron resonance. The condition for the cyclotron resonance between the waves and the particles can be written as

$$\omega - k_{\parallel} v_{\parallel} = n\Omega , \tag{1}$$

where ω and $k_{\parallel}$ are the wave frequency and the parallel component of the wave vector k; $v_{\parallel}$ is the parallel component of the particle velocity; $\Omega = qB_0/mc$ is the cyclotron frequency of the charged particle; B_0 is the magnetic field; q and m are the particle charge and mass, respectively; c is the speed of light; and n is an integer equal 0, ± 1, ± 2,.... The $k_{\parallel} v_{\parallel}$ term is the Doppler-shift effect due to the particle motion relative to the wave. The case of $n = 0$ corresponds to the Landau resonance. When the condition of Equation (1) is satisfied, the waves and particles remain in phase, leading to energy and momentum exchange between them.

The cross-field diffusion rate of electrons and ions, due to their resonant interaction with the magnetic component of electromagnetic waves, can be written as [*Tsurutani and Thorne, 1982*; *Thorne and Tsurutani, 1991*; *Tsurutani and Lakhina, 1997*]

$$D_{\perp,B} = 2\eta \left(\frac{B}{B_0} \right)^2 D_{max} , \tag{2}$$

where B is the amplitude of the wave magnetic field at the resonant frequency given by Equation (1), η is a dimensionless scaling factor indicating what fraction of time the particles stay in resonance with the waves, and

$$D_{max} = \frac{cmv_{\perp}^2}{2eB_0} \tag{3}$$

is the Bohm diffusion rate [*Bohm, 1949*]. Here, $v_{\perp}$ denotes the perpendicular velocity of the charged particles relative to the ambient magnetic field, B_0. Similarly, the cross-field diffusion rate due to the electrostatic waves is given by

$$D_{\perp,E} = 2\eta \left(\frac{E}{B_0} \right)^2 \left(\frac{c}{v} \right)^2 D_{max} , \tag{4}$$

where E is the amplitude of the wave electric field at the resonant frequency given by Equation (1), and v is the magnitude of the particle velocity.

For the magnetopause boundary-layer parameters, $B_0 \approx 50\,\text{nT}$, $N \approx 20\,\text{cm}^{-3}$, and protons of energies $\sim 1\,\text{keV}$ can be in cyclotron resonance with the wave at $\omega/\Omega_p \sim 1$ (Ω_p is the proton cyclotron frequency), i.e., at frequencies close to 1 Hz. Using the observed power at these frequencies in wave magnetic [*Gendrin, 1983*; *Rezeau et al., 1986*] and electric [*Tsurutani et al., 1981*] components, we get $D_{\perp,B} = 260\,\text{km}^2\text{s}^{-1}$ and $D_{\perp,E} \approx 4\times10^2\,\text{km}^2\text{s}^{-1}$ for $\sim 1\,\text{keV}$ protons, with negligible cross-field diffusion for 1 keV electrons.

It should be noted that theoretical models of either a viscous momentum transfer [*Axford, 1964*] or mass diffusion across the magnetopause [*Sonnerup, 1980*] require a kinematic viscosity or diffusion coefficient comparable to $10^3\,\text{km}^2\text{s}^{-1}$ to account for the observed magnetopause boundary-layer thickness. The broadband waves show orders-of-magnitude variability in the power-spectral densities for both magnetic and electric components [*Gurnett et al., 1979; Tsurutani et al., 1981*; *Gendrin, 1983*; *LaBelle and Treumann, 1988*; *Tsurutani et al., 1989*]. This could lead to substantially different rates of cross-field diffusion, thereby explaining the observed variations in the thickness of the magnetopause boundary layer.

The intense broadband waves in the boundary layers can cause rapid isotropization of both the electron and ion distributions. *Tsurutani et al.* [*1981*] found a strong correlation between intense broadband waves in the magnetopause boundary layer and 1-6 keV electrons and protons. The observed wave power was found to be sufficient to scatter the 1-6 keV electrons and protons near the limit of strong pitch-angle diffusion. On using the measured spectrum of the ISEE 1 electrons and ions, and integrating from 1 to 10 keV, the precipitated energy flux into the atmosphere was estimated to be $\approx 1.0\,\text{erg}\,\text{cm}^{-2}\text{s}^{-1}$ [*Tsurutani et al., 1989*]. These numbers are comparable to the dayside auroral energy input. Therefore, it appears that resonant cyclotron interactions between the waves and particles in the magnetopause boundary layer can provide a reasonable explanation for the nearly continuous presence of dayside aurora.

Several processes other than the resonant wave-particle interaction can also produce isotropization of both the electron and ion distributions. Stochastic scattering of particles by microscopic plasma turbulence can lead to an anomalous collision frequency, ν_{an}, in a collisionless plasma [*LaBelle and Treumann, 1988*]. In particular, current-driven plasma instabilities can generate sufficiently high anomalous collision frequencies in space plasmas [*Dum and Dupree, 1970*; *Treumann et al., 1991*]. Anomalous collision frequencies, in turn, can produce anomalous cross-field diffusion of the plasma. It is suggested that the lower-hybrid drift instability may produce diffusion coefficients large enough to explain the thickness of the magnetopause boundary layer [*Treumann et al., 1991, 1995*]. Observations from ISEE 1 and Geotail also indicate that the amplitudes of the magnetopause boundary-layer waves are large enough to provide the dissipation required for reconnection to occur [*Cattell et al., 1995*].

It has been proposed that the low-frequency part of the BEN, which carries most of the wave energy, can cause the diffusion of warm PSBL ions. *Grabbe and Eastman* [*1984*] and *Dusenbery and Lyons* [*1985*] argued that BEN can be generated due to ion-beam instabilities, and that the excited electrostatic waves possibly scatter warm ions in the PSBL. *Dusenbery and Lyons* [*1989*] evaluated the ion-diffusion coefficients due to the ion-beam instabilities. They solved the unmagnetized dielectric function with ion beams, and showed that ion-sound waves can be generated under the coexistence of cold and hot ion-beam components. They also examined the parametric dependence of the diffusion rate of ions due to the resonance with excited ion-sound waves, and concluded that significant diffusion should occur, resulting in isotropization of the warm ions in the PSBL.

6. TIME-DOMAIN STUDIES OF BOUNDARY-LAYER WAVES

6.1 PSBL Electrostatic Solitary Waves

Most of the above observational results and data analysis of the broadband boundary-layer waves were discussed in the frequency domain. Only recently, high-time-resolution boundary-layer wave data have been analyzed. *Matsumoto et al.* [*1994*] analyzed the waveform data of the plasma-wave instrument onboard the Geotail spacecraft, and they discovered that the broadband electrostatic noise (BEN) in the plasma-sheet boundary layer was not at all broadband, but instead consisted of discrete bipolar solitary pulses in the time domain. The broadness of the BEN frequency spectra arises from the solitary waveforms, and the pulse widths decide the uppermost frequency of the spectra. The important finding from Geotail strongly influenced the prevalent ideas about "broadband" plasma waves in other boundary layers, especially the plasma-wave studies by Polar and FAST.

Figure 10a shows the frequency-time spectrogram of BEN, observed in the PSBL by Geotail at ($-118R_E$, $4.3R_E$, $0.7R_E$) on April 1, 1993. The coordinate system is GSM. Intense BEN spectra can be clearly seen, extending all the way to the electron-plasma frequency ($f_{pe} \sim 2$ kHz) during the intervals from 13:30 to 13:36 (UT), from 13:41 to 13:53 (UT), from 13:54 to 14:00 (UT), and from 14:12 to 14:22 (UT). Figure 10b shows waveforms observed by the waveform capture (WFC) receiver at 13:55:43.241 (UT). The observed waveforms were coherent, and had pulse widths of about 2 ms. Because the most frequently observed BEN emissions have isolated pulse waveforms and no obvious corresponding magnetic component, *Matsumoto et al.* [*1994*] termed them "PSBL electrostatic solitary waves (PSBL ESW)," after their waveforms. However, the PSBL ESW mainly contribute to the high-frequency portion of the BEN spectra [*Kojima et al.*, *1994*, *1997*]. Wave amplitudes of the ESW at lower frequencies, as shown in Figure 10, are too small to explain the low-frequency component.

A likely generation mechanism for BEN is based on the nonlinear evolution of the electron-beam instabilities, leading to the formation of the isolated Bernstein-Greene-Kruskal (BGK) [*Bernstein et al.*, *1957*] potential structures, which well reproduce the observed electrostatic solitary waveforms [*Matsumoto et al.*, *1994*; *Omura et al.*, *1994*, *1996*, *1999*; *Kojima et al.*, *1999*]. An example of the time evolution of the bump-on-tail instability, obtained by the one-dimensional computer simulations, is shown in Figure 11. The right and left panels display the time series of electron-phase diagrams and reduced electron-velocity distributions. The vortices shown in the left panel are electron holes, formed by trapped electrons due to isolated electrostatic potentials, which are generated by the nonlinear evolution of the bump-on-tail instability.

6.2 PCBL and Auroral-Zone Wave: Solitary Electric Field Structures

The high-time-resolution measurements of the broadband plasma waves in the PCBL region by Polar, and in the auroral ionosphere by FAST, have just started to come out, and they have given very useful information on the fine structure of the boundary-layer waves. Recent results on

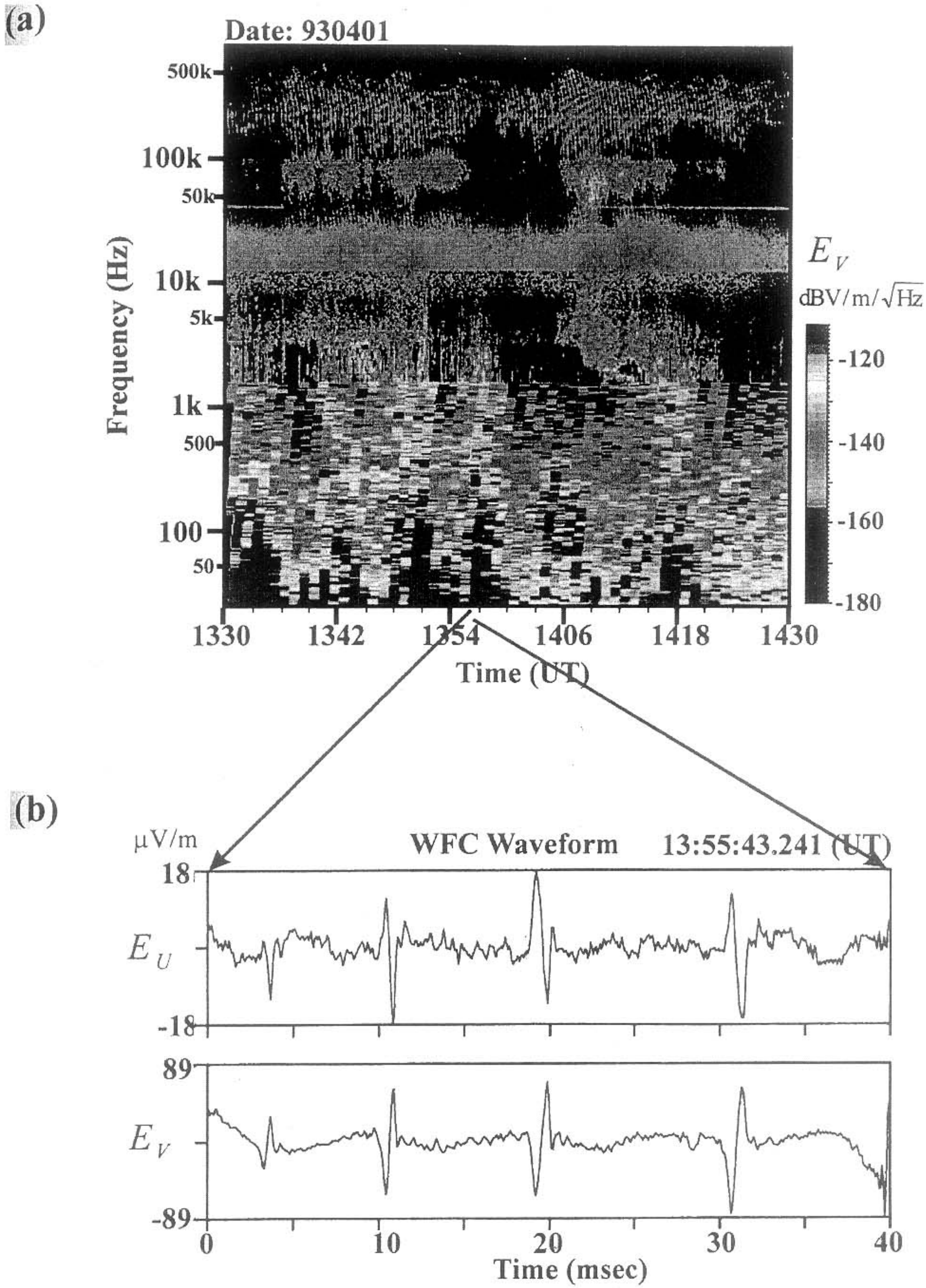

Figure 10. A typical frequency-time spectrogram of the BEN and corresponding ESW waveforms (Plate 3 from [*Lakhina et al., 2000a*]) (see also Plate 11).

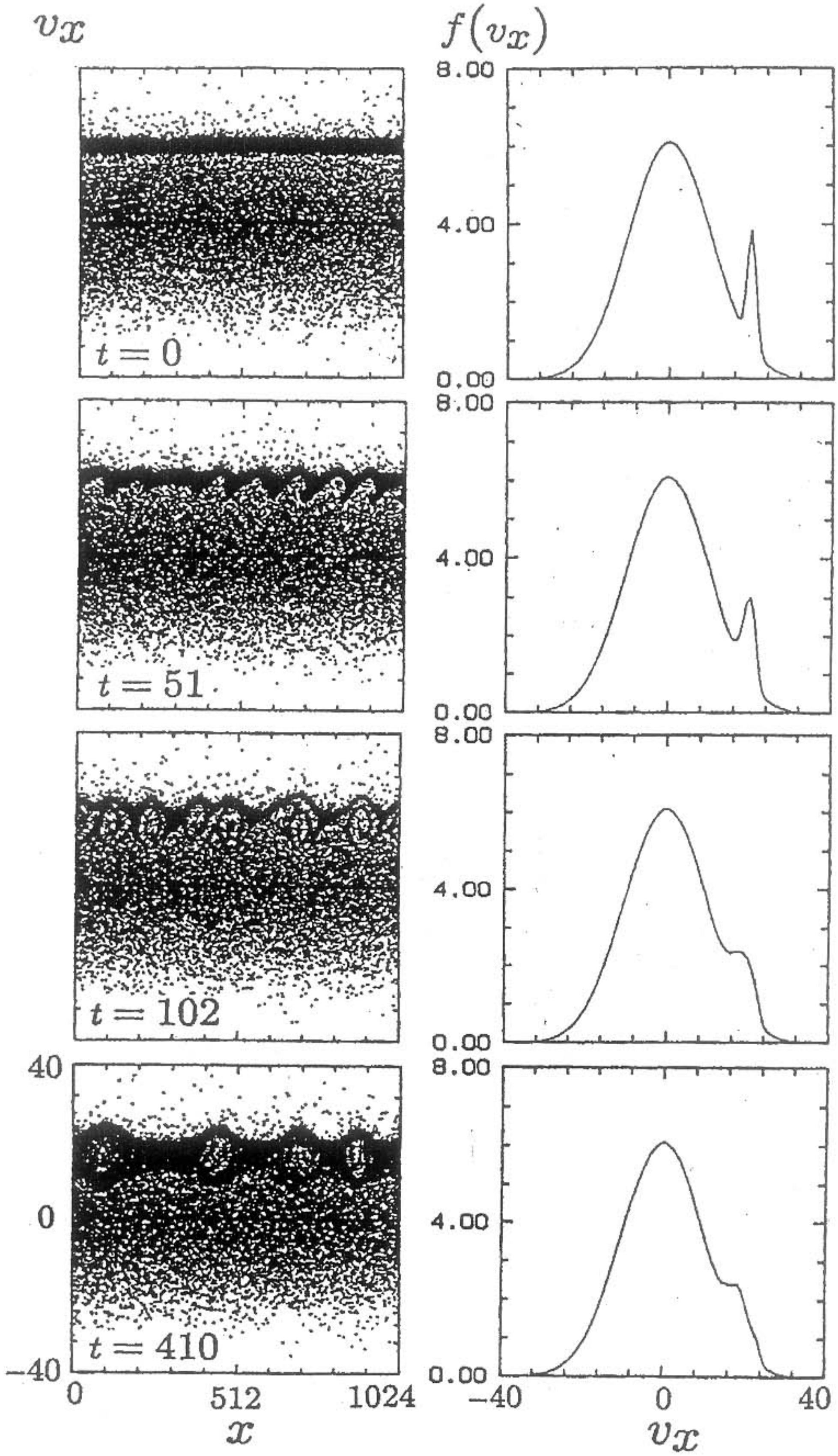

Figure 11. The time evolution of the bump-on-tail instability. The right and left four panels show the time series of electron-phase diagrams and the electron-velocity distribution (Figure 7 in [*Omura et al., 1996*]).

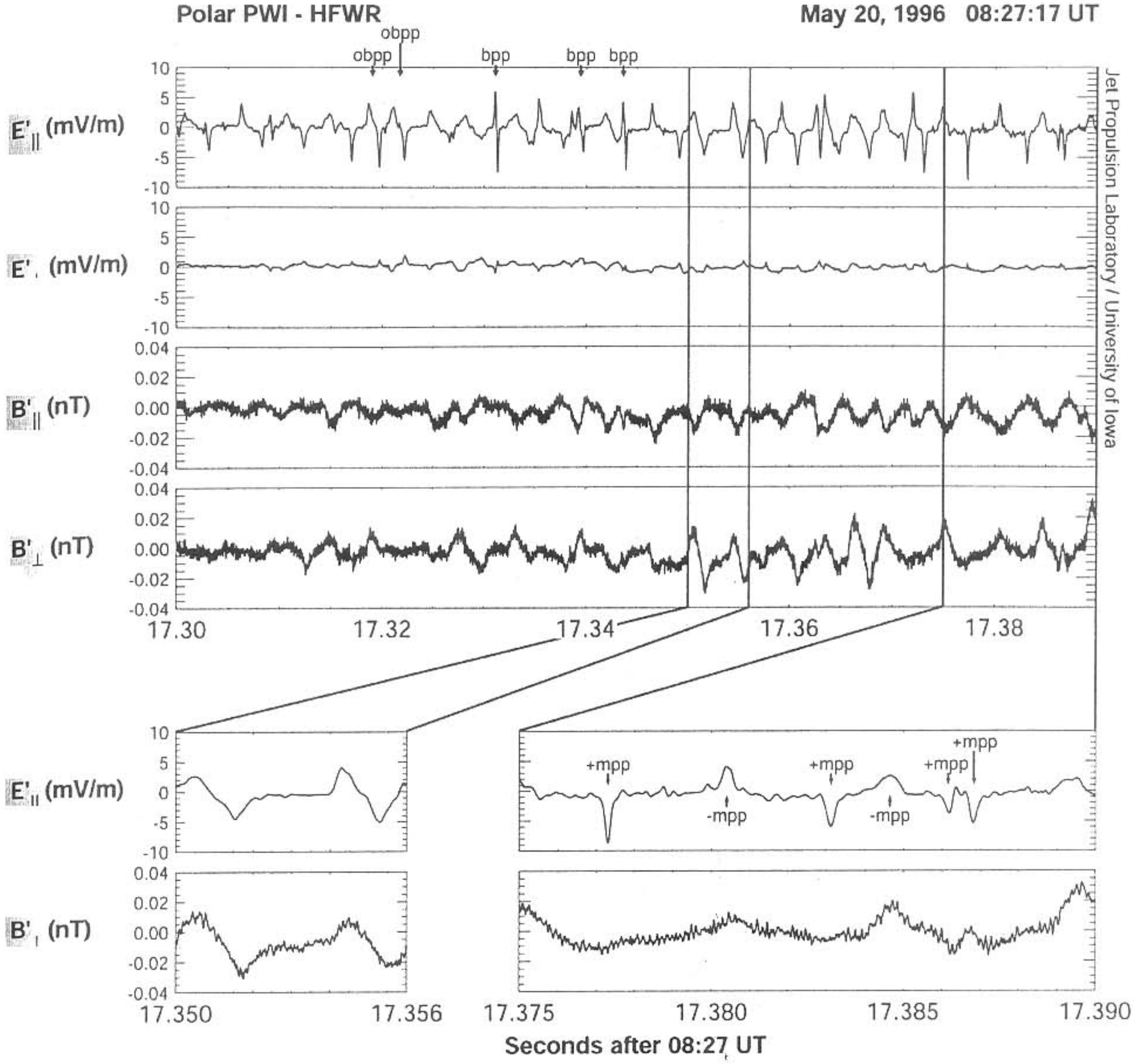

Figure 12. Bipolar (bpp), offset bipolar (obpp), and monopolar (mpp) wave structures in the parallel electric field component (from *Tsurutani et al.* [*1998b*], Figure 3).

the PCBL waves, using the high time resolution of the Polar, indicate the presence of three types of intense electrostatic signals, namely, bipolar solitary pulses, waves at $\sim 4\times10^2$ to 6×10^3 Hz (lower-hybrid waves), and narrowband waves at ~ 10 kHz (electrostatic waves near the electron-plasma frequency, probably upper-hybrid waves) [*Tsurutani et al., 2001*]. Figure 12 shows an example of large-amplitude bipolar pulses (bpp) in the parallel electric component of the wave, similar to PSBL BEN, at high altitudes ($\sim 6 R_E$) [*Franz et al., 1998, 2000*; *Tsurutani et al., 1998b; Cattell et al., 1998*] as well as at low altitudes ($\sim$ 1-2 R_E) [*Mozer et al., 1997*]. There are magnetic signatures associated with these electric pulses. Offset bipolar pulses (obpp), where the positive pulse does not follow immediately after the negative pulse but is delayed somewhat, are also seen in this figure. Further, the monopolar pulses (mpp) in the parallel electric field component are seen in the right-hand inset of Figure 12. The monopolar pulses are found to alternate between one polarity and the opposite polarity, and to occur in pairs. These three types of parallel electric fields can be explained by a model involving a one-dimensional electron hole and the surrounding neutralizing charge [*Tsurutani et al., 1998b*]. *Franz et al.* [*2000*] have shown that electron holes observed by Polar are roughly spherical for $f_{ce}/f_{pe} > 1$, becoming more oblate (with the perpendicular scale larger than the parallel scale) with decreasing f_{ce}/f_{pe}. A comparison of the characteristics of solitary waves, such as their scale sizes and velocities, observed by Polar in the high-latitude cusp, polar-cap, and plasma-sheet boundary layers, has been given by *Cattell et al.* [*1999*].

Similarly, recent measurements from FAST have revealed the presence of intense localized electrostatic wave structures at altitudes of 2000 to 4000 km on the auroral field lines [*Ergun et al., 1998a, 1998b*]. *Muschietti et al.* [*1999*] have interpreted these solitary structures in terms of BGK phase-space electron holes drifting along the magnetic-field lines. *Goldman et al.* [*1999, 2000*] have given an explanation for these bipolar structures in terms of nonlinear two-stream instabilities, a mechanism similar to that of the PSBL BEN proposed by *Omura et al.* [*1996*] and *Kojima et al.* [*1997*].

7. CONCLUSION

The magnetopause and the plasma-sheet boundary layers, which are formed due to solar-wind-magnetosphere interaction, are the site of broadband plasma waves. We have described the main characteristics of the broadband plasma waves observed in these boundary layers. The waves are spiky signals, spanning a broad frequency range from less than the ion-cyclotron frequency to probably greater than the electron-cyclotron frequency. *Tsurutani et al.* [*2001*] have shown that the latitudinal-local-time distribution of PCBL waves is similar to the Feldstein auroral oval. Since the nature of the PCBL wave electric structures is found to be similar to those detected at lower altitudes by experiments on Viking, Freja and FAST, they concluded that these waves are on the auroral-zone magnetic field lines. These same magnetic field lines most likely map into the low-latitude boundary-layer (LLBL) region of the magnetopause. The magnetopause and polar-cap boundary-layer waves could scatter the energetic electrons and ions into the atmospheric loss cone. The energy flux precipitated into the auroral ionosphere is sufficient to excite dayside diffuse aurora. Since the magnetopause and polar-cap boundary field lines map to the auroral oval, based on the energy flux precipitated by the waves, it is suggested, that these boundary-layer waves could be responsible for the diffuse dayside aurora. It is known that the diffuse aurora often occurs equator-ward of the region of auroral arcs. But it is not clear whether the two are really distinct, or if the separation between them is simply due to the diffuse aurora being much dimmer than the discrete aurora [*Meng*, *1978*, *1981*]. Further, the broadband plasma waves may not be restricted only to the boundary layers. Rather, the regions of most intense wave events have been used to define the boundary layer [*Tsurutani et al.*, *2001*]. It is found that the regions where the waves were most intense also contained BEN.

The broadband plasma waves discussed here seem to be ubiquitous to the plasma-flow boundaries. For example, BEN has been observed in the magnetotail [*Cattell et al.*, *1986*; *Gurnett and Frank*, *1977; Matsumoto et al.*, *1994; Kojima et al.*, *1994*], on cusp and auroral field lines (*Scarf et al.*, *1972*; *Gurnett and Frank*, *1977*, *1978*; *Pottelette et al.*, *1990*; *Dubouloz et al.*, *1991a; Kasahara et al.*, *2001*], and in the magnetosheath [*Anderson et al.*, *1982*]. The magnetotail BEN emissions are correlated with ion and electron beams, whereas auroral-region BEN emissions are usually associated with ion conics and field-aligned electron beams. Generation mechanisms, in terms of electron-acoustic solitons and nonlinear electron-acoustic waves, have been suggested for

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