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Observations of electrostatic solitary waves associated with reconnection by Geotail and Cluster

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Abstract

We report the observations of Electrostatic Solitary Waves (ESWs) associated with reconnection by the Wideband Plasma Wave Receiver of Cluster and the Wave From Captures of Geotail near the diffusion region at dayside magnetopause and in the magnetotail region. ESWs have been observed along the plasma sheet boundary and near diffusion region, both earthward and tailward of the x-line. Cluster II detected the ESWs simultaneously at both side of neutral sheet by three of the four satellites. By carefully checking the data of particle, field and wave, we studied the temporal and spatial evolution of ESWs, their relative locations with reconnection layer and the relationship with the distributions of electrons. Comparison with full particle simulations with the observations, we discuss the importance of these solitary waves in collisionless reconnection and their possible generation mechanisms is provided.

Keywords: Space plasma physics: nonlinear phenomena; Space plasma physics: magnetic reconnection; Space plasma physics: electrostatic structures; Magnetospheric physics

1. Introduction

The importance of waves in the reconnection process has long been of interest, the possible role of a number of different wave modes during magnetopause reconnection was examined by Treumann et al. (1995) and Winske et al. (1995). ESW, characterized by their solitary bi-polar pulses in the electric field parallel to the background magnetic field, have been observed in many regions of the magnetosphere, including the distant magnetosheath, the magnetotail, the Earth' bow shock, the magnetopause, the cusp, along auroral field lines, and in the high altitude polar magnetosphere et al. (Kojima et al., 1994; Matsumoto et al., 1994a; Matsumoto et al., 1997; Cattell et al., 1999; Pickett et al., 2003; Mozer et al., 1997; Ergun et al., 1998; Pottelette and Treumann, 1998; Bale et al., 1998).

Recently, satellite observations (Cattell et al., 2002; Farrell et al., 2002; Matsumoto et al., 2003; Deng et al., 2004) and three-dimensional particle simulations (Drake et al., 2003) and have provided evidence that electron holes may play an important role in reconnection by scattering and energizing electrons. The formation of small scale E-field structures (ESWs), their stability, and their role in the global organization of the plasma and in the energy redistribution between fields and particles, are questions

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of general interest in space physics. The Cluster satellites can simultaneously measure electric field waveforms at several locations within the current layer, they provide the good opportunity to study the role of electron holes and other wave modes in the dynamics of reconnection. In this paper, we report the observations of ESWs associated with reconnection near the diffusion region and along the plasma sheet boundary layer by Geotail and Cluster.

2. Observations

2.1. ESWs associated with reconnection observed at dayside magnetopause by Geotail

ESW observed associated with reconnection at Dayside magnetopause by Geotail Data from three GEOTAIL investigations were used in this study: the Plasma Wave Instrument (PWI) (Matsumoto et al., 1994a), the Low Energy Particle Experiment (LEP) (Mukai et al., 1994), and the Magnetic Field Investigation (MGF) (Kokubun et al., 1994). Analyses of the high-time-resolution data from the PWI Multi-Channel Analyzer (MCA) and Wave-Form Capture (WFC) receivers have provided important new insights into space physics plasma wave research. Here we concentrate on one event when a well-studied Coronal Mass Ejection struck the Earth on January 10, 1997, as GEOTAIL skimmed along the dayside magnetopause and observed three-dimensional multiple x-line magnetic reconnection (Deng and Matsumoto, 2001). Electrostatic Solitary Waves (ESW) and Amplitude Modulated Electrostatic Waves (AMEW) were detected associated with reconnection.

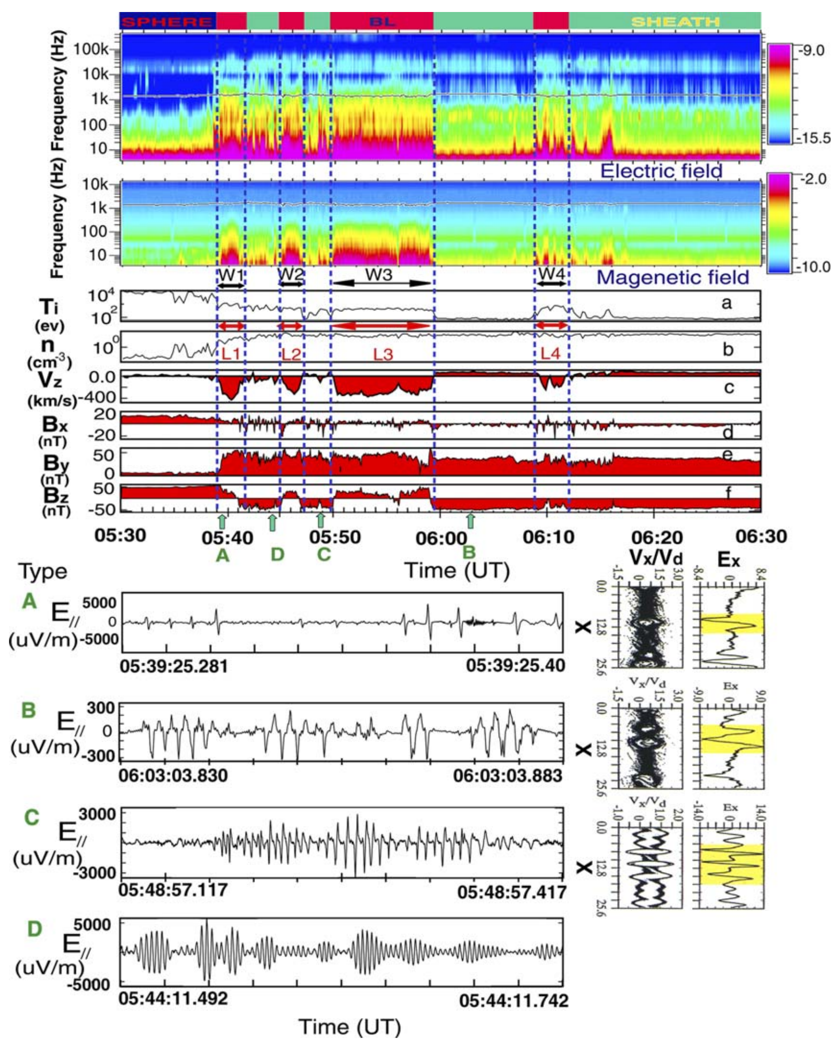

Fig. 1. Observations by GEOTAIL from 05:30 UT to 06:30 UT on January 10, 1997. The upper part is the dynamic frequency-time spectrogram of the electric and magnetic fields data from the Multi-Channel Analyzer (MCA). The middle part shows the ion temperature, density, plasma flow speed component V_z, and magnetic field components B_x, B_y and B_z, respectively. At the bottom, Types A–C are several typical electrostatic wave forms of the Broadband Electrostatic Noise (BEN) associated with reconnection, which show close similarity with those found in particle simulations shown on the right. Type D is the highly-amplitude-modulated electrostatic wave (AMEW). The four waveform panels have full scale time spans of 119, 53, 300 and 250 ms, respectively.

Fig. 1 shows relevant observations by GEOTAIL from 05:30 UT to 06:30 UT as it traversed the dayside magnetopause. The color-coded bar at the top identifies the regions. Below that are the dynamic frequency-time spectrograms of the electric and magnetic field data from the MCA. The black and white line slightly above 1 kHz in both spectrograms is the electron cyclotron frequency determined from the MGF. In the next several panels the dayside magnetopause boundary crossing is identified by the orientational change of the magnetic field component B_z and distinct changes of the ion temperature (T_i) and the density (n). The magnetic reconnection event is recognized by the observation of high-speed spikes of the plasma velocity component V_z (labeled L_1, L_2, L_3 and L_4) and the bipolar signature of the B_x magnetic component (Paschmann et al., 1979; Sonnerup, 1979).

Though the WFC operates only 8.7 s every 5 min (Matsumoto et al., 1994a), we do have data from the WFC at critical periods when the three-dimensional transient magnetic reconnection took place near the spacecraft at the dayside magnetopause boundary layer. We observed a variety of waveforms in this reconnection event. At the bottom of Fig. 1, some typical waveforms of the electric field components are plotted. The green arrows show when these samples were acquired. The data clearly show that the BEN waves are not random noises (such as "white noise"). Instead, they are composed of coherent structure. Type A ESW are a series of large amplitude electric bipolar pulses. Type B ESW are offset bipolar pulses. The positive part of the pulses does not follow immediately the negative part. There is a short time interval of almost zero field plateau between the negative and positive parts. Type C ESW are multiple bipolar electric field pulses that form amplitude-modulated wave trains. Type D ESW are highly amplitude-modulated electrostatic waves (AMEW). All of these ESW and AMEW are purely electrostatic waves. At the right-hand of the bottom of Fig. 1, three waveforms at different spatial positions in the evolution of electron beam instability from an electrostatic particle simulation (Matsumoto et al., 1994b) are shown for comparison. It is noteworthy that the above-described waveforms of ESW emissions as a function of time show very close similarity with those found in simulations as a function of space.

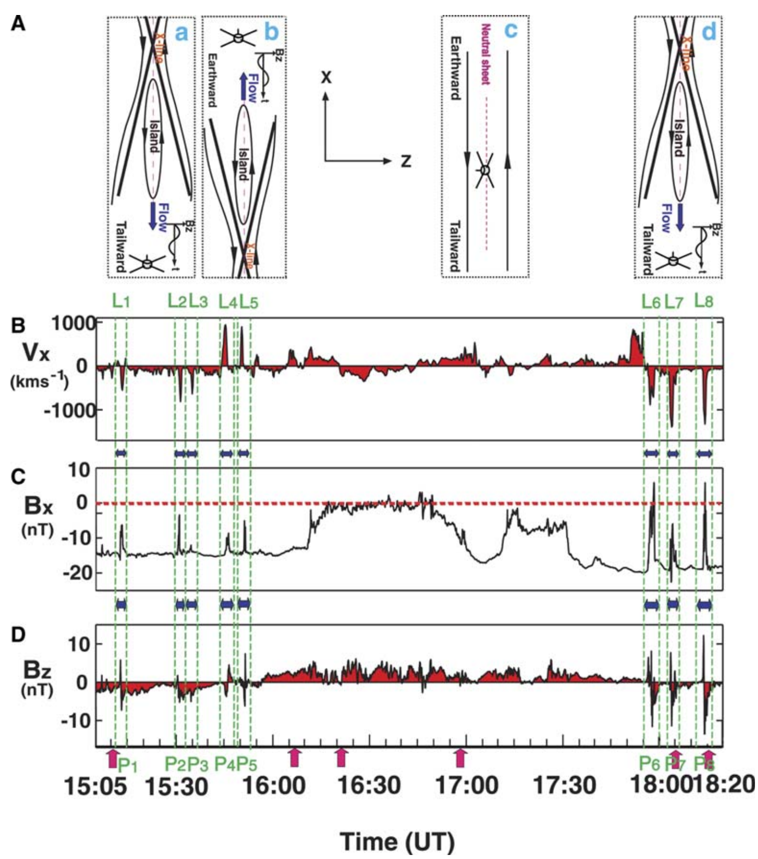

Fig. 2. Plasma and magnetic field data observed by GEOTAIL as it traveled through the Earth's magnetotail about 38 Earth radii behind the Earth during the interval from 15:05 to 18:20 UT on 11 December 1994. Part A contains schematic diagrams of the collisionless reconnection configuration and the relative location of GEOTAIL during the observations. Part B is a plot of the plasma flow speed component of V_x. Parts C and D are plots of the magnetic field components B_x and B_z, respectively. Large tailward, then Earthward and finally tailward plasma jets are observed as the spacecraft traveled from the tailward side to the earthward side, and then to the tailward side of the x-line.

2.2. ESWs associated with reconnection observed in the magnetotail region by Geotail

On December 11, 1994 the GEOTAIL spacecraft encountered an active reconnection diffusion region around the x-line in the Earth's magnetotail. Fig. 2 shows a summary of the observations by the GEOTAIL satellite for the interval from 15:05 to 18:20 UT on 11 December 1994. Part A contains schematic diagrams of the collisionless reconnection configuration and the relative location of GEOTAIL during the observations. Three interesting features were observed: One is quadrupole pattern of the out-of-plane B_y magnetic field component during the passage of magnetic islands and the crossing of the neutral sheet. The second is a direction reversal of the electron beams in the vicinity of the separatrix of the magnetic topology of reconnection. The third is a clear plasma flow reversal. Fig. 3 shows the typical waveforms of the electric field components of the Broadband Electrostatic Noise (BEN). The $E_{\|}$ and $E_{\perp}$ are the electric field components parallel and perpendicular to the ambient magnetic field B projected on to the antenna plane. The ESWs shown in Fig. 3 are observed both near neutral sheet and around the plasma sheet boundary.

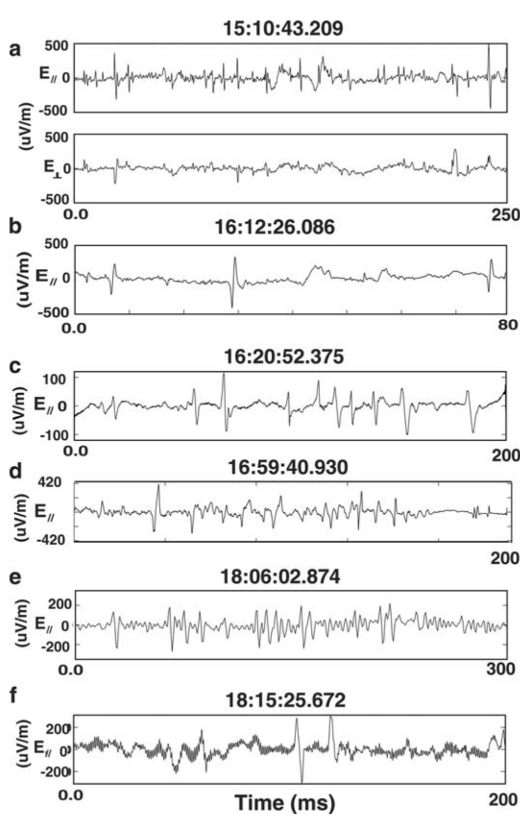

Fig. 3. Typical electrostatic waveforms of the Broadband Electrostatic Noise (BEN) associated with reconnection. The Electrostatic Solitary Waves (ESWs) are observed both near neutral sheet and around the plasma sheet boundary. The $E_{\|}$ and $E_{\perp}$ are the electric field components parallel and perpendicular to the ambient magnetic field B projected on to the antenna plane.

2.3. Observations of ESWs along plasma sheet boundary layer and near diffusion region by Cluster

ESWs have been observed during waveform captures on three of the four Cluster satellites during several plasma sheet encounters. An overview of the interval of interest during several plasma sheet encounters near x-line regions is shown in Fig. 4 during the period of 09:20 UT to 10:00 UT on October 1, 2001. During the reconnection period, we have more than one-hour wave from data from the Cluster Wideband (WBD) Plasma Wave Receiver (Gurnett et al., 1997). WBD is a high-time-resolution waveform receiver. The 9.5, 19 and 77 kHz bandwidth filters that are available to WBD provide time resolutions between successive samples of about 36.5, 18.2, and 5 μs, respectively.

The ESWs have been observed by three of the four Cluster satellites. Fig. 5 shows simultaneous Cluster WBD waveforms from three spacecrafts C1, C2 and C4 for a 10000 ms period of time on 01 October 2001. WBD samples in the 77 kHz with duty cycle mode, which leads to the data gaps observed in the figure. At the bottom the snapshots show examples of solitary waves observed at the times indicated at the top of the panels respectively. The beauty of the 77 kHz filter is that it can resolve pulses with very short time durations. The amplitudes of the majority of both types of pulses vary from less than 1 to about 10 mV/m peak-to-peak. A number of isolated solitary waveform types have been observed, i.e., monopolar pulses, bipolar pulses, tripolar pulses, and offset bipolar pulses near the diffusion region associated with reconnection by Cluster and Geotail. The waves near the electron plasma frequency with highly amplitude modulated were also observed.

2.4. Observations of ESWs and electron beams

In order to understand the relationship of ESWs with reconnection, and the mechanism of ESWs, we have examined the structure and dynamics of the plasma sheet and observation of electrons during this interval and the relative locations of the satellites. We have checked the waveform data of WBD and the electron distribution functions from PEACE of Cluster II. We carefully checked the characteristics of the electron distribution functions when ESWs are observed through the whole one-hour period of the observation of WBD. On the other hands, by looking through the electron distribution functions every four seconds, when electron beams are detected by PEACE, we checked if there are ESWs observed by WBD at that time. In general, by combining and checking the data of magnetic field, plasma temperature and density, as well as the dis-

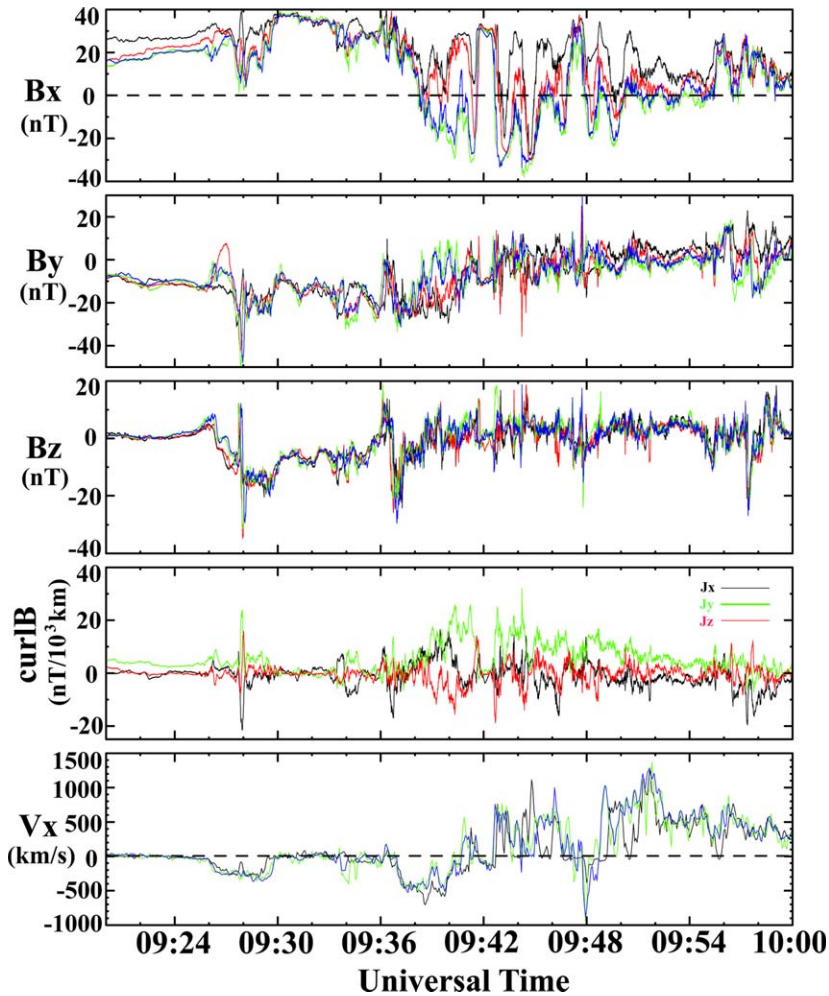

Fig. 4. Overview of the interval of interest of several plasma sheet encounters near x-line regions during the period of 09:20–10:00 UT on October 1, 2001. From top to bottom are the components of the magnetic field, the components of curl B vector, and the x-component of proton bulk velocity versus time.

tribution functions of electrons and ions, solitary waves tents to be observed along the plasma sheet boundary layer and near x-lines region when an intense narrow electron beam or narrow counter-streaming beams occurred. When satellites are closer to the center of current sheet, they observed hot, fairly isotropic distributions or observed distributions with very broad pitch angle beams and no solitary waves were observed. The relationship of the solitary waves to electron distributions can be seen in Fig. 6, which plots sample electron distributions obtained during the waveform captures. The electron observations shown herein were obtained by the PEACE instrument (Johnstone et al., 1997). The top four distributions were obtained at a time when solitary waves were observed (Fig. 6(a)–(d)), whereas the lower two were obtained during intervals without solitary waves (Fig. 6(e) and (f)).

We study the waveforms of ESWs and corresponding electron velocity distribution functions observed by Geotail. When a serious of ESWs was observed, we find enhanced fluxes of high-energy electrons flowing along the ambient magnetic field. Fig. 7 shows the electron distribution functions in the velocity plane which is defined such that the Y-axis is the magnetic field directions ($V_{\parallel}$) and the X-axis is the direction of the convection velocity ($V_{\perp}$) with reference to the spacecraft frame. The phase space density is scaled by color-coding on logarithmic scale. As the time resolution of the particle measurements of Geotail is 12 s, while the growth time of the electron beam instability is of the order of several milliseconds, what we find is a diffused electron beam after the saturations of the instability. The strong enhancement of the electron flux over the wide range of the velocity space make it difficult to identify the diffused electron beam carry the ESW. By checking the electron distribution function of Geotail, it is found that the ESWs are observed in the presence of a hot thermal electron distribution function. The Langmure wave, on the other hands, are observed when an enhancement of electron flux is found with temperature of the thermal elec-

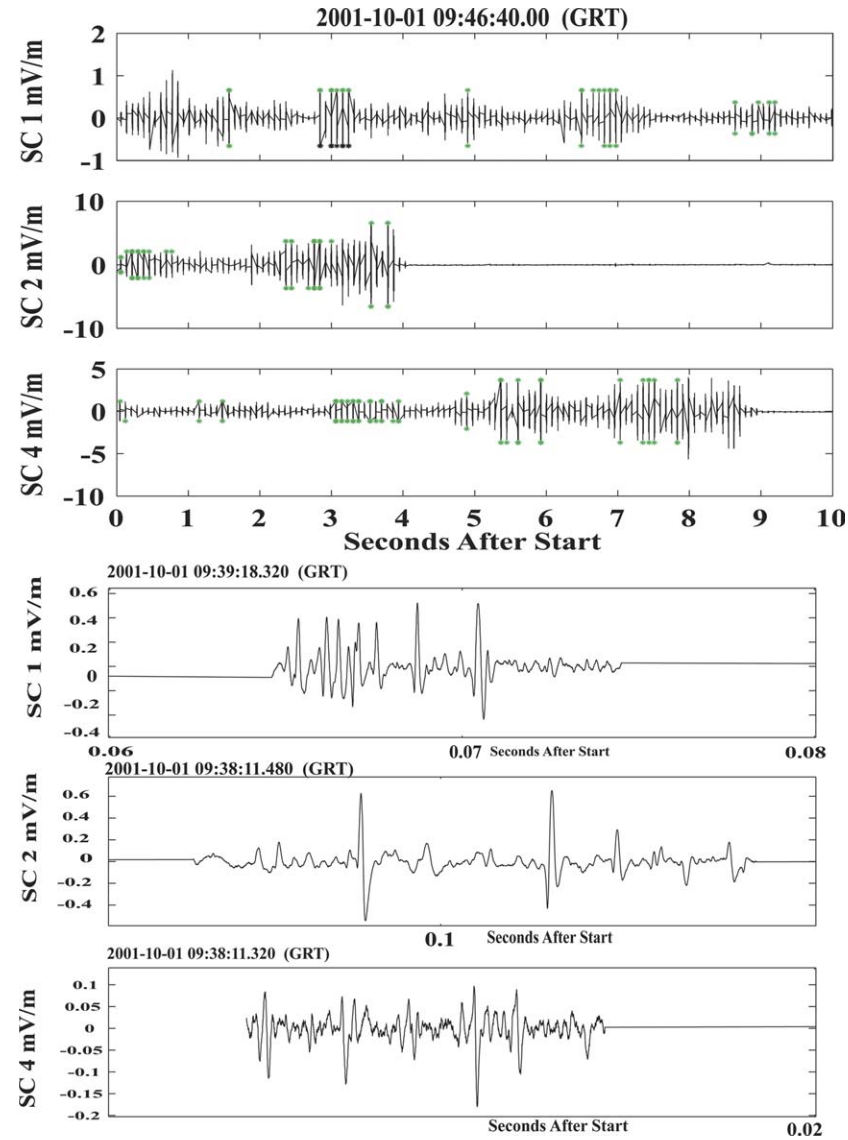

Fig. 5. Simultaneous Cluster WBD waveforms from three spacecrafts C1, C2 and C4 for a 10000 ms period of time on October 01, 2001. The bottom show the snapshots of ESWS observed at the times indicated at the top of the each panels, respectively.

trons are small. Such tendency is consistent with simulations (Matsumoto et al., 1999). By assuming that the electron velocity distribution consists of isotropic bulk thermal electrons and nonthermal electrons (Omura et al., 1996), we have found good correlation between the propagation direction of the ESWs and the direction of the enhanced high-energy electron flux.

3. Discussions and conclusions

A recent study of reconnection in a thin current sheet with Hall effect suggest that microphysics is not so important in reconnection, it is still necessary to understand the mechanism that decouples the electrons from the magnetic field, as well as heating and acceleration processes. We have observed large amplitude ESWs and other wave modes at dayside magnetopause boundary and in the magnetotail region by Cluster and Geotail. The ESWs were observed along the plasma sheet boundary layer and near the diffusion region, both earthward and tailward of the x-line during magnetotail current sheet crossings associated with passage of a reconnection x-line. A number of isolated solitary waveform types have been observed, i.e., monopolar pulses, bipolar pulses, tripolar pulses, and offset bipolar pulses. Many other wave modes have been also observed associated with reconnection.

ESWs have been observed during waveform captures of WBD by three of the four Cluster satellites SC1, SC2 and SC4 on the event of October 1, 2001. The ESWs were observed around plasma sheet boundary layer and near

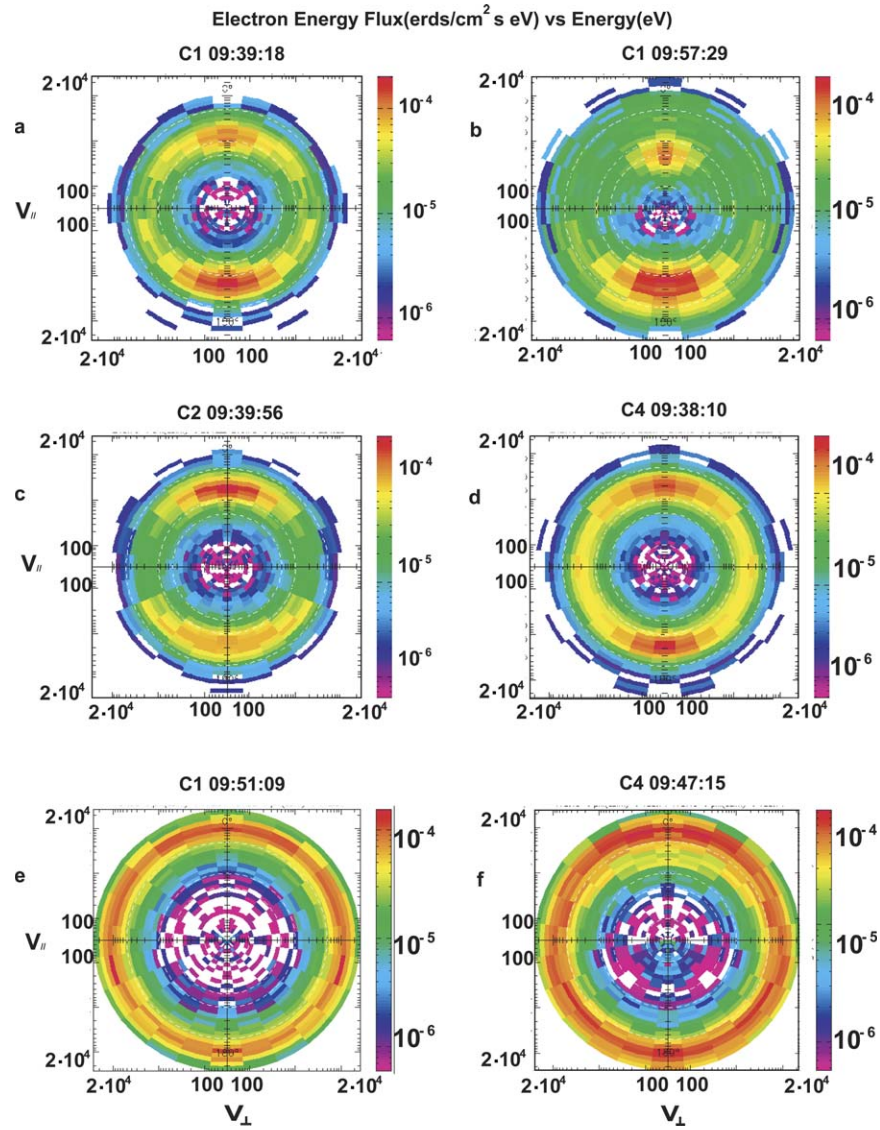

Fig. 6. The typical electron pitch angle distributions obtained from PEACE during intervals with ESWs (top four panels of a, b, c, d) and without ESWS (bottom two panels of e, f). Pitch angle of 0° is at the top of each panel, and 180° is at the bottom. Distributions are in energy flux plotted versus energy from 100 to 20,000 eV.

diffusion region at both side of x-line as well as simultaneously at both side of the neutral sheet by WBD. The same event has been studies by checking the waveform data from EFW (Cattell, 2005), where there was only short period of waveform data from EFW and the ESWs were only seen by two satellites SC2 and SC4.

We also found that changing of the polarities of ESWs as Geotail moved from tailward side to Earthward side of the x-line region or reverse. For the Earthward side with Earthward flow (Fig. 3(b) and (d), the main polarity of ESWs is from negative value to positive value while for the tailward side with tailward flow, the main polarity of ESWs is from positive value to negative value Fig. 3(a),(c),(e) and (f)), which is consistent with the source of electron beams from the reconnection site. However, we also find quick change of the polarities of ESWs in very shout time (ms). We should also note that electron beams can result not only from reconnection, but also from polarization (or gradient) drift (Genot et al., 2004).

WBD does not have the capability on one spacecraft of determining direction of propagation and the velocity of the solitary wave, which is required in order to determine directly whether a bipolar solitary wave is an electron or ion hole. By checking the EFW data on the same event of 2001 January 10, Cattell et al. (2005) have found many features of ESWs are in agreement with particle simulations of Drake et al. (2003). They found that positive potential structures of ESWs are consistent with electron phase space holes were observed in the regions predicted by the simulations. The measured velocity, scale sizes, and circular shape of the holes match those

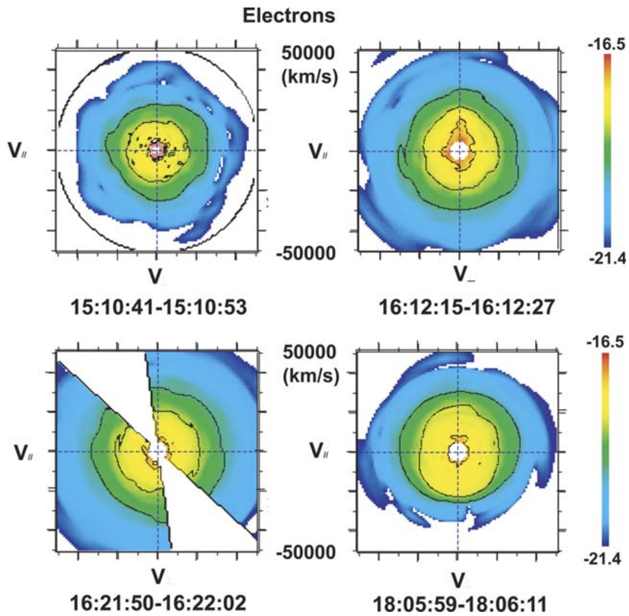

Fig. 7. The distribution functions of electrons associated with the observations of ESWs. The distribution functions of electrons are the slices of the three-dimensional distribution functions in a plane which is defined such that the Y-axis is the magnetic field directions ($V_{\|}$) and the X-axis is the direction of the convection velocity ($V_{\perp}$) with reference to the spacecraft frame. The phase space density is scaled by color-coding on logarithmic scale shown at the right-hand side.

obtained from the simulations. The predicted hole speed, V_{h}, is approximately equal to $(m_{\mathrm{e}}/m_{\mathrm{i}})^{1/3}V_{\mathrm{de}}$, where V_{de} is the electron beam speed. This prediction is ~900–3500 km/s, compared to the observed speeds of 700–2500 km/s. The predicted hole scale size $L_{\mathrm{h}} = V_{\mathrm{de}}/f_{\mathrm{pe}} \sim 4$–14 km, compared to the observed $> \sim 3$ km (Cattell et al., 2005). Timing of the electron holes observed by Cluster yields speeds that are consistent with the Buneman instability (the order of a tenth of the beam velocity) but are much lower than would be predicted by the Omura simulations. However, only a small fraction of the observed holes can be timed due to limitations in the instrument. The rest were moving too fast or occurred when the angle between both pairs of the electric field probes and the magnetic field was too large for accurate timing. Therefore, the currently available Cluster statistics on electron holes during reconnection events are not adequate to definitely conclude that the speed is always a fraction of the beam speed because only a small fraction of the solitary waves could be timed. It is noteworthy that the above-described waveforms of ESW emissions as a function of time show very close similarity with those found in simulations as a function of space. It seems that the Buneman instability and the beam-plasma instability are the major cause of such small-scale structure formation.

The good agreement between the Cluster data and the predictions of reconnection simulations suggest that the observed microphysics, including electron holes and large amplitude waves, play critical role in dynamics of reconnection in the magnetosphere. The nonlinear coherent structures may provide important dissipation in the electron diffusion region during magnetic reconnection. The fact that similar observations have been made at the magnetopause suggests that microphysics is critical to an understanding of reconnection throughout the magnetosphere. It is worth to note that we have observed ESWs associated with reconnection with and without guild magnetic field while Drake et al. have shown that ESWs can exits only with the guild of magnetic field line. Whether these structures are the cause or consequence of the acceleration is not clear, and the nature of the electric field configuration which leads to the most efficient acceleration is still controversial (Genot et al., 2004; Büchner, 1999). More over, these electron beams are not always present at the exact times when the solitary waves are observed on Cluster, because the time resolution of the Cluster PEACE instrument is also not sufficient when compared to solitary waves that occur on time scales on the order of several ms. Further, the PEACE angular resolution is not narrow enough to determine whether the beams that are occasionally observed simultaneously with the solitary waves are actually beams, or whether they are unresolved conics. Preliminary analysis of several other reconnection events provides evidence that cross-scale coupling may be important because Alfven waves, lower hybrid waves, whistler waves and solitary waves are often seen together, which will be our future research. It is quite important to combine EFW data with WBD data of Cluster and Geotail observations for detailed investigation of the property of ESWs, and relationship between reconnection and ESWs and other waves with the help of computer simulations.

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