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## Dynamics and waves near multiple magnetic null points in reconnection diffusion region

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[1] Identifying the magnetic structure in the region where the magnetic field lines break and how reconnection happens is crucial to improving our understanding of three-dimensional reconnection. Here we show the in situ observation of magnetic null structures in the diffusion region, the dynamics, and the associated waves. Possible spiral null pair has been identified near the diffusion region. There is a close relation among the null points, the bipolar signature of the Z component of the magnetic field, and enhancement of the flux of energetic electrons up to 100 keV. Near the null structures, whistler-mode waves were identified by both the polarity and the power law of the spectrum of electric and magnetic fields. It is found that the angle between the fans of the nulls is quite close to the theoretically estimated maximum value of the group-velocity cone angle for the whistler wave regime of reconnection.

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### 1. Introduction

[2] Magnetic reconnection, a process through which magnetic energy can be converted into kinetic and thermal energy in plasma, is responsible for many dynamic phenomena throughout the universe. Observations in solar and

other astrophysical plasmas indicate that reconnection is essentially three-dimensional (3-D), and there is observational evidence that reconnection involving a 3-D null point may be at work in some solar flares [Fletcher *et al.*, 2001] and solar eruptions [Aulanier *et al.*, 2000; Ugarte-Urra *et al.*, 2007], and current growth at 3-D nulls has been observed in the laboratory [Bogdanov *et al.*, 2004]. Recently, Xiao *et al.* used the data from the four-spacecraft Cluster constellation to first identify the presence of single magnetic null [Xiao *et al.*, 2006] and null pair [Xiao *et al.*, 2007]. It is quite important to study the null structures in the diffusion region and the dynamic and associated waves [Finn, 2006; Dorelli *et al.*, 2007].

[3] Here we report the observation of multiple 3-D magnetic nulls in the diffusion region observed by the Cluster constellation on 1 October 2001. The topological and physical properties of the nulls and the related 3-D reconnection are revealed by the high-resolution data of fields, particles, and waves.

### 2. Observations and Analysis

[4] We have surveyed the data from 2001 to 2003, and found several good events where nulls and multiple nulls structures have been identified in the diffusion region. Here we concentrate on the event of 1 October 2001.

[5] During the interval 093:00–09:50 UT on 1 October 2001, Cluster was located in the pre-midnight magnetotail, and crossed the neutral sheet several times. High-speed proton flow, with reversal from tailward to Earthward and then to tailward was detected during the multiple crossings.

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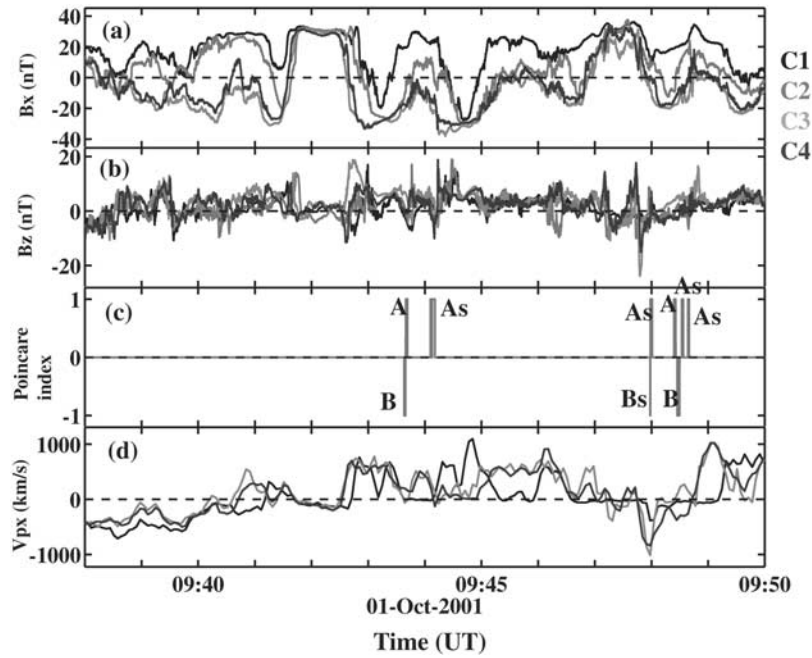
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**Figure 1.** Cluster measurements and calculated Poincaré index during the interval of 09:38–09:50 UT on 1 October 2001. From top to bottom: Components of the magnetic field (FGM) (a) Bx and (b) Bz, (c) the Poincaré index, and (d) X component of the proton bulk velocity (CIS) versus time in the GSM coordinate system.

Figure 1 shows the magnetic field components Bx and Bz, the Poincaré index, and the X component of the bulk proton flow respectively. Magnetic field data are obtained from the Fluxgate Magnetometer (FGM) [Balogh *et al.*, 2001], and low-energy ions data from the Cluster Ion Spectrometry (CIS) experiment [Reme *et al.*, 2001], and high-energy electrons data are provided by RAPID [Wilken *et al.*, 2001]. This event was well studied by several authors with different respects of reconnection in the ion diffusion region, including the Hall magnetic field [Runov *et al.*, 2003], thin current sheet with Hall electric field [Wygant *et al.*, 2005], electrostatic solitary waves [Cattell *et al.*, 2005; Deng *et al.*, 2006], electron acceleration [Imada *et al.*, 2007], and null pair [Xiao *et al.*, 2007].

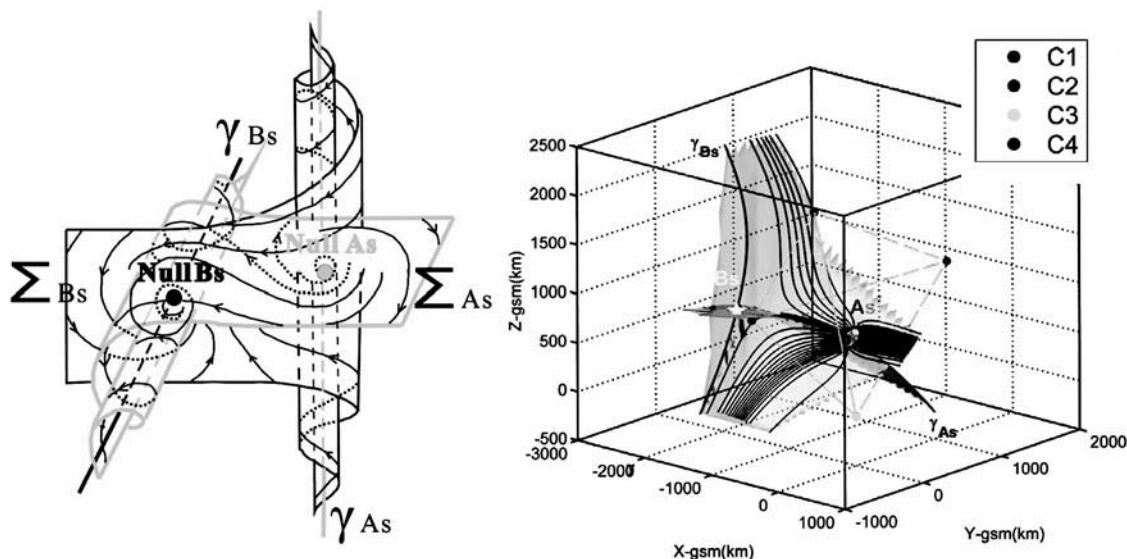
[6] During the several crossings of the neutral sheet, a cluster of magnetic null points are identified near the diffusion region as shown in Figure 1c by using the topological degree method to calculate the Poincaré index [Lau and Finn, 1990; Greene, 1988; Zhao *et al.*, 2005]. The 22 Hz high-resolution magnetic field data are used to

analyze the 3-D structure in the vicinity of the null. The linear interpolation methods are used to confirm the existence of nulls in the barycenter of Cluster [Greene, 1992]. The total relative error in calculating  $\delta B$  is characterized by the ratio of  $\nabla \cdot B/|\nabla \times B|$  with several hundredths. It is found that the A/As nulls and B/Bs nulls often appear adjacent to each other. Clusters of nulls containing both A-type and B-type null points have also been found in simulations [Dorelli *et al.*, 2007].

[7] We analyzed the eigenvalues and eigenvectors of magnetic fields in the vicinity of the null points, and assessed the relative orientations of the spines and fans of the nulls to check whether there are some near by positive and negative nulls that are connected to each other via magnetic separators [Longcope and Cowley, 1996; Priest and Titov, 1996]. Near 09:48:00 UT, two spiral nulls of As (negative spiral null) and Bs (positive spiral null) were identified during the crossings of the neutral sheet and their characteristics are shown in Table 1. Note there is large bipolar magnetic structure near the spiral nulls. If the two

**Table 1.** Characteristics of the Null Pair of Bs and As Near 09:48:00 UT

Time	09:47:58.68–09:47:58.685	09:47:59.04–09:48:0.75
Poincaré index	-1	1
Type	Bs	As
$ \nabla \cdot B $	0.0027	0.0015
$ (\nabla \cdot B)/(\nabla \times B) $	0.166	0.094
Eigenvalues	-0.00612, 0.00167 + i0.00326, 0.00167 - i0.00326	0.00661, -0.00330 + i0.00398, -0.00330 - i0.00398
Eigenvectors	(0.792 -0.583 -0.181), (-0.782 0.216 - i0.479 0.292 - i0.166), (-0.782 0.216 + i0.479 0.292 + i0.166)	(-0.251 -0.476 0.843), (0.788 -0.428 - i0.385 -0.007 - i0.218), (0.788 -0.428 + i0.385 -0.007 + i0.218)
Angles estimated locally by the eigenvectors of nulls	1° for $\gamma_{As}$ and $\sum_{Bs} \gamma_{Bs}$ and 2° $\sum_{As}$	
Angles obtained from reconstructed fields by the fitting method	1.3° for $\gamma_{As}$ and $\sum_{Bs}$ at null As $\gamma_{Bs}$ and 2.4° for $\sum_{As}$ at null Bs	



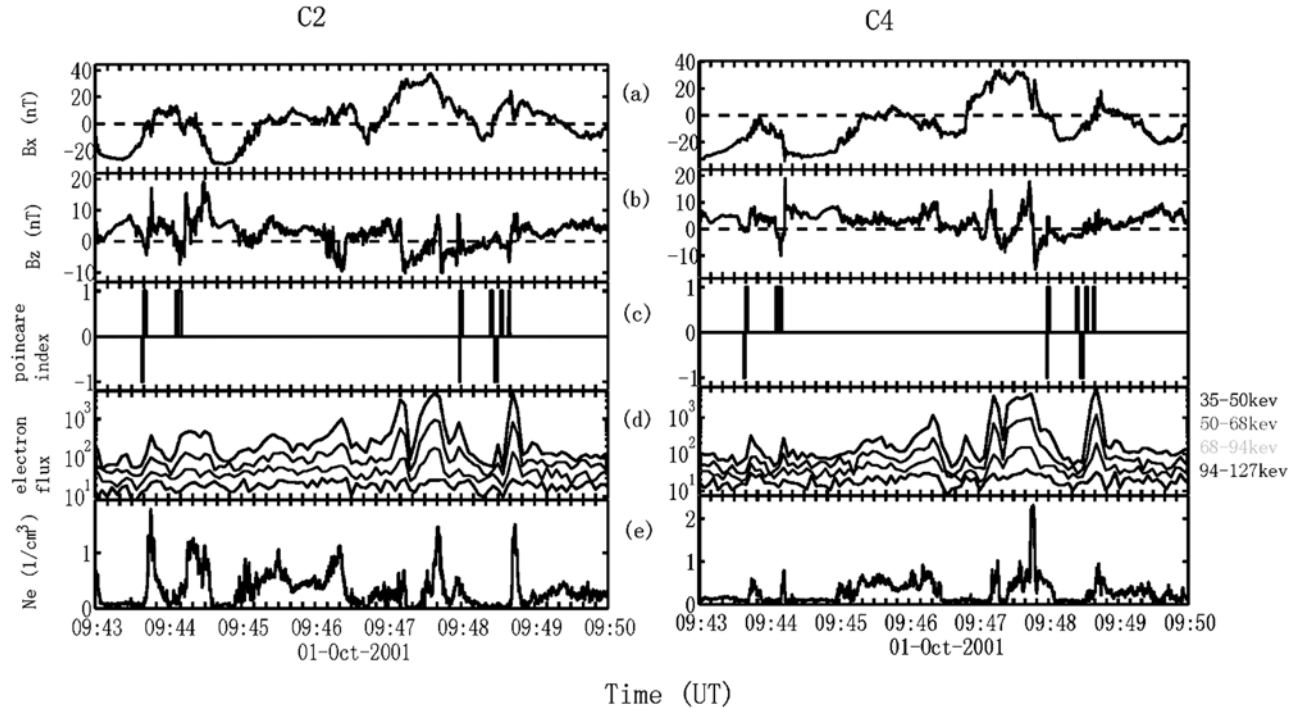
**Figure 2.** Three-dimensional reconnection structures. The left part is the structure of the spiral null pair of negative spiral null point  $A_s$  and positive spiral null point  $B_s$ . The fan surface of the spiral null  $A_s$  wraps the spine of the spiral null  $B_s$  whereas the fan surface of  $B_s$  wraps the spine of  $A_s$ . The right part is the structure of the magnetic field lines near the null  $A_s$  and null  $B_s$  at the time of 09:48:05 UT obtained by the fitting method. There are spiral structures near null  $A_s$  and null  $B_s$ . Near the null  $B_s$ , the spine  $\gamma_{B_s}$  of null  $B_s$  approaches the magnetic field lines in the fan surface  $\Sigma_{A_s}$  of null  $A_s$ , and near the null  $A_s$ , the  $\gamma_{A_s}$  approaches the magnetic field lines in the fan surface  $\Sigma_{B_s}$ . The angles between the spines and fans are  $2.4^\circ$  and  $1.3^\circ$ , respectively.

nulls are connected by a fan-fan separator as a spiral null pair, the fan surface of a null will wrap the spine of the other null. This means that if we move the spine of one null to the position of another null, the spine will lay on the fan surface of the null point. It is interesting to note from Table 1 that the spine  $\gamma_{A_s}$  of the null  $A_s$  is perpendicular to the normal vector of the fan surface  $\Sigma_{B_s}$  of null  $B_s$ , and the angle between  $\gamma_{A_s}$  and  $\Sigma_{B_s}$  to be almost zero (about  $1^\circ$ ). The similar relation has been also found between the spine of null  $B_s$  and fan surface of  $A_s$  indicating that the null  $A_s$  and null  $B_s$  are a possible spiral null pair. However, for spiral nulls, the spines and fan surfaces are largely curved. If two spiral nulls are connected as a spiral null pair, the fan surface of one spiral null will wrap around the spine of the other spiral null. On the left part of Figure 2, it shows the 3-D magnetic field structure of spiral null pair of  $A_s$ - $B_s$  [Cai *et al.*, 2001]. In order to investigate the cosurface relations between the two spiral nulls of  $A_s$  and  $B_s$  at the locations of the two nulls respectively, we use the fitting method [He *et al.*, 2008] to fit the recorded 4 vectors with 12 magnetic field components simultaneously measured by the Cluster satellites. This method uses a summation of 12 functions, which includes ten spherical harmonic functions and a function taken from the Harris current sheet model [Harris, 1962], together with a constant background field. We depict the global magnetic field structures around null  $A_s$  and null  $B_s$  by following the magnetic field lines starting from the two nulls. On the right part of Figure 2, it shows the results of the magnetic structures around null  $A_s$  and null  $B_s$  at the time 09:48:05 UT by the fitting method. It can be seen that the magnetic fields near the null  $A_s$  and null  $B_s$  have spiral structures. Near the location of null  $B_s$ , the  $\gamma_{B_s}$  approaches the magnetic field lines in the fan surface

of  $\Sigma_{A_s}$ , and the angle between  $\gamma_{B_s}$  and fan surface of  $\Sigma_{A_s}$  is  $2.4^\circ$ , which is quite near the results of  $2^\circ$  estimated by the eigenvectors locally in Table 1. The similar relation have been also found between  $\gamma_{A_s}$  and  $\Sigma_{B_s}$  near the location of null  $A_s$  with the angle of  $1.3^\circ$ , which also is quite near the results of  $1^\circ$  estimated by the eigenvectors locally.

[8] Figure 3 shows the relation between the magnetic nulls (c), the bipolar structures of  $B_z$  (b), and enhancement of electron flux (d) for SC2 (left) and SC4 (right) respectively. The flux of energetic electrons up to 100 keV peaks has been observed near null points. There is close relation among the locations of the magnetic nulls, the bipolar structures of  $B_z$  and enhancement of electron flux.

[9] The instruments included in the Cluster Wave Experiment Consortium (WEC) [Roux and de la Porte, 1988] are quite useful to characterize plasma waves and turbulence and to assess their role in the ‘‘anomalous’’ behavior of thin critical layers where the MHD approximation is broken. Figure 4 shows the wave characteristics of the waves observed near the magnetic null points in the frequency range between 10 Hz and 4 kHz observed by SC2 during the interval 09:47:40–09:49:00 UT on 1 October 2001 [Cornilleau-Wehrin *et al.*, 2001; Santolik *et al.*, 2003]. The solid lines represent the electron cyclotron frequency obtained from the FGM data. Near the nulls there is an enhancement of waves from low frequency to high frequency (d) and large electric fields (b). At frequencies above approximately 60 Hz, we detect right-hand polarized waves, most probably whistler-mode waves (red in Figure 4e). Figure 4f shows that average Poynting flux can have both positive and negative parallel component in different time intervals. There are waves in different directions, not just a single plane wave (g). We fast Fourier transformed the EFW



**Figure 3.** Close relationship among the magnetic nulls, the bipolar structure of  $B_z$ , and enhancement of electron flux for cluster 2 (left) and cluster 4 (right). From the top are (a) the X component of the magnetic field, (b) the Z component of the magnetic field, (c) the Poincaré index, (d) the flux of energetic electrons up to 100 keV, and (e) the electron density, respectively.

and FGM data to produce the power spectra at low frequencies and time averaged the STAFF electric and magnetic field spectra over the time interval to yield the spectra at high frequencies [Petkaki *et al.*, 2006]. Figure 5 shows the resultant energy density spectrum of electric and magnetic fields of SC2 during the period of 09:48:23 ~ 09:48:28 UT. The vertical dashed red and blue lines are the electron and ion cyclotron frequencies  $f_{ce}$  and  $f_{ci}$  respectively. The whistler waves have been confirmed by the power law of the spectrum of electric and magnetic fields. For the broadband spectral component of whistler waves in a high beta plasma, we have  $\omega \sim k^2$  and for a given angle between  $k$  and  $\vec{E}$ , it is found that  $|\vec{B}|^2 \sim |\vec{E}|^2/\omega$ , which is consistent with the observed difference  $a_B - a_E = 1$  in the power spectral slopes by linear fitting.

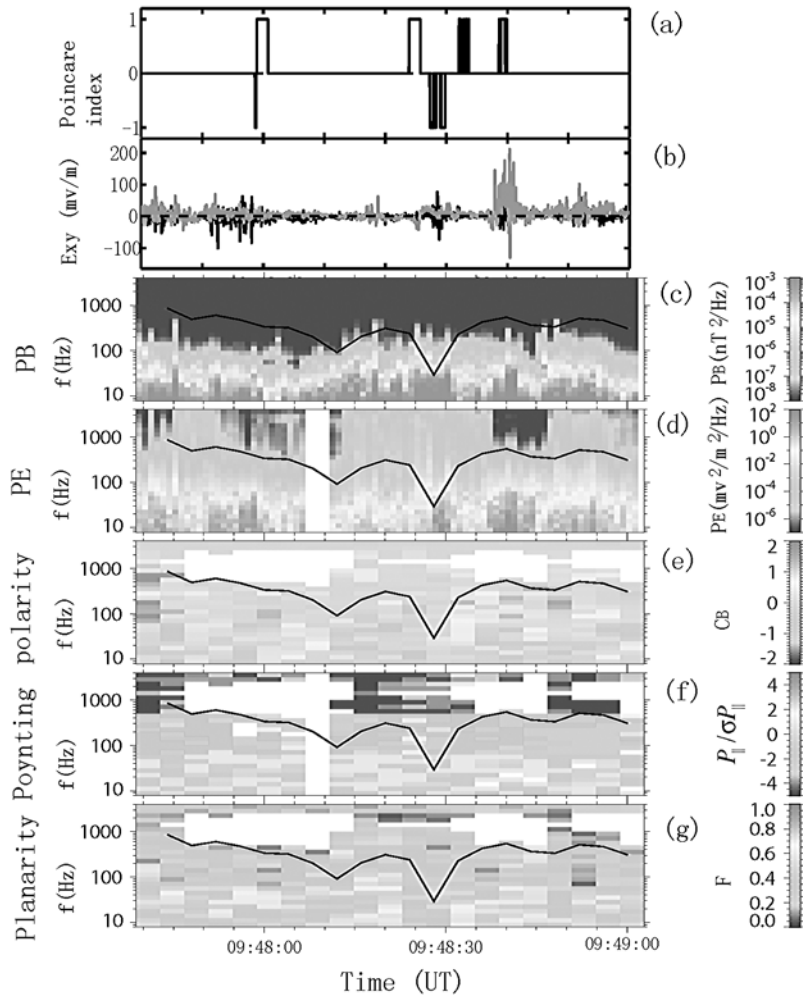
[10] Recently Singh [Singh, 2007] showed that the geometrical feature of the exhaust region that diverges out of the localized diffusion region is determined by the group velocity of the disturbances, and the value of  $19.5^\circ$  is nearly independent of the wave frequency or timescales as long as they fall in the whistler wave regime. We have checked the angles of the fans of A-B-As structure, we found that the angles between the fans of the nulls are about  $42^\circ \sim 44^\circ$  with the half-cone angle of  $21^\circ \sim 22^\circ$ . Note that this value is quite close to the theoretically estimated maximum value  $19.5^\circ$  of the group-velocity cone angle of whistler waves in diverging magnetic reconnection structures.

### 3. Conclusions and Discussions

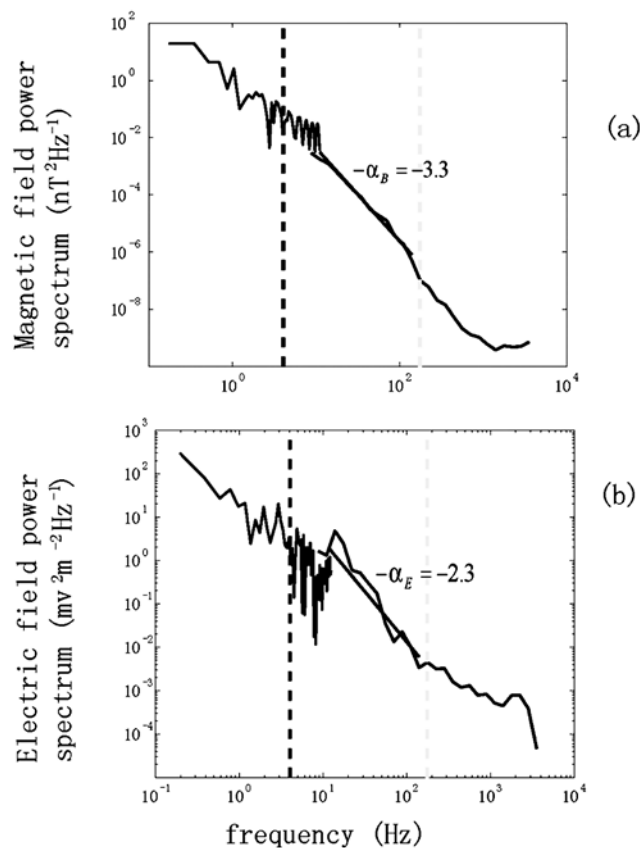
[11] 3-D structure of reconnection and the decoupling of electron and ion motion at small spatial scales is profoundly

important. Changing the topology of magnetic field lines, which is necessary for releasing energy during magnetic reconnection, requires some form of dissipation to break the frozen-in condition. Closing to the diffusion region the role is taken over by either the whistler-mode or kinetic Alfvén wave [Bale *et al.*, 2002; Carter *et al.*, 2002; Deng and Matsumoto, 2001; Drake *et al.*, 2003; Farrell *et al.*, 2002; Huba *et al.*, 1977; Rogers *et al.*, 2001].

[12] In this paper, the possible spiral null pair of As-Bs has been identified near the diffusion region. The spiral type of As (negative spiral null) and Bs (positive spiral null) can be decided according to the eigenvalues of the Jacobian matrix of the vector magnetic fields locally. The local characteristics of spines and fan surfaces of the spiral nulls of As and Bs, and the relation between them could be determined and estimated by the eigenvectors locally. The global magnetic field structures around the null As and null Bs could be demonstrated by the fitting method, and we have followed the magnetic field lines by the fitting method and checked the relation of spine and fan surface at the null points respectively. By combining the local analysis of the null types of As and Bs on the basis of the eigenvalues and eigenvectors, and checking the global magnetic structures obtained by the fitting method, the null As and null Bs near the diffusion region are highly possible spiral null pair. The close relation between the location of 3-D null points, the bipolar signature of the Z component of the magnetic field and enhancement of the flux of energetic electrons up to 100 keV strongly suggest that reconnection involving one or multiple 3-D nulls occurs. Near the null structures, whistler-mode waves were identified by both the polarity and the power law of the spectrum of electric and magnetic



**Figure 4.** Wave characteristics observed by C2 during the period of 09:47:40–09:49:00 UT on 1 October 2001. From top to bottom are (a) the Poincaré index, (b) the X and Y components of electric fields, (c, d) power-spectral densities of magnetic and electric fields, and (e) the indicator of the sense of polarization. For the left circularly polarized field, the ellipticity is  $-1$ , a value of  $+1$  corresponds to the right circular polarization. A linearly polarized field has a zero ellipticity. (f) Normalized component of the Poynting vector parallel to the ambient magnetic field, and (g) the planarity of the magnetic field polarization. Solid lines on the dynamic spectra show the electron cyclotron frequency.



**Figure 5.** Magnetic field energy density spectrum from FGM (red) and STAFF (blue) and electric field spectrum from EFW (red) and STAFF (blue) from SC2 for the interval 09:48:23–09:48:28 UT. The observed difference  $a_B - a_E = 1$  in the power law spectral slopes is consistent with theoretical prediction.

fields. It is found that the angle between the fans of nulls is quite close to the theoretically estimated maximum value of the group-velocity cone angle for whistler wave. The 3-D structures and evolution of the nulls, the related dynamics of 3-D reconnection, the role of waves, where and how the charged particles are accelerated will be studied in the future by combining observations with simulations [Drake et al., 2006; Pontin et al., 2007; Cairns and McMillan, 2005].

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