Multiple cusps during an extended northward IMF period with a significant B_y component

Q.-G. Zong,[1,2] H. Zhang,[3] T. A. Fritz,[3] M. L. Goldstein,[4] S. Wing,[5] W. Keith,[4] J. D. Winningham,[6] R. Frahm,[6] M. W. Dunlop,[7] A. Korth,[8] P. W. Daly,[8] H. Rème,[9] A. Balogh,[10] and A. N. Fazakerley[11]

Received 22 November 2006; revised 15 August 2007; accepted 11 October 2007; published 24 January 2008.

[1] On 21–22 March 2001, four cusp-like regions were observed consecutively in about five hours by all four Cluster spacecraft when the interplanetary magnetic field (IMF) was northward with a significant B_y component. All four cusp-like encounters were characterized by turbulent magnetic fields, high-density plasma, and plasma flow significantly slower than the magnetosheath level. The cusp-like regions are associated with thermalized, bidirectional distributed plasma electrons. The first encountered cusp is the main cusp; the other three cusp-like regions are temporal effects. The normal velocities v_n at boundary interfaces (exit from the cusp) are found to be almost three times larger than that at boundary interfaces (entry into the cusp). The boundary normal, velocity, and timing analysis for six clear boundaries of the last three cusps obtained by all four spacecraft indicates that they are most likely one boundary shifting in the dawn-dusk direction between the dayside magnetosphere/trapping region and the cusp region. So the Cluster spacecraft have been observing the same cusp, and it appeared as four cusp-like regions due to possible magnetospheric oscillations. Oscillations with a period of 22 min are observed by the Cluster spacecraft in the high-latitude region, which is in agreement with the cold-dense plasma sheet fluctuations (20 min period) observed by the Geotail satellite. Multiple cusps observed by Cluster and the wavy-like structures in the dusk low-latitude boundary layer observed by Geotail simultaneously suggest the whole magnetosphere is oscillating during northward IMF.

Citation: Zong, Q.-G., et al. (2008), Multiple cusps during an extended northward IMF period with a significant B_y component, *J. Geophys. Res.*, *113*, A01210, doi:10.1029/2006JA012188.

1. Introduction

[2] The magnetopause is a transition layer between the magnetosheath and magnetosphere where the magnetosheath pressure is balanced by the magnetosperic pressure. Therefore magnetosheath pressure variation can move the position of the magnetopause back and forth [e.g., *Sibeck et al.*, 1991]. It has been observed that the interplanetary magnetic field (IMF) can affect the position of the magnetopause. The magnetopause moves closer to the Earth when the IMF B_z is southward [*Sibeck et al.*, 1991; *Petrinec and Russell*, 1993]. Oscillations of the magnetospheric boundaries could also be driven by the IMF rotations [*Laakso et al.*, 1998]. However, all of those are dealing with low-latitude or subsolar magnetopause. Very few studies have addressed the variation of the position of the high-latitude boundary and the cusp. Multiple cusp phenomena have been observed [*Wing et al.*, 2001; *Zong et al.*, 2004; *Pitout et al.*, 2006]. The multiple cusps have been suggested to be either spatial [*Wing et al.*, 2001] or temporal effect (windsock effect) [*Zong et al.*, 2004] or a combination of a spatial feature and temporal effect [*Zong et al.*, 2004].

[3] The spatial and temporal variations of the high-altitude cusp is more complex than usually expected. The spatial variations of the cusp have been focused on the dispersion of plasma ions in the cusp region [*Wing et al.*, 2001; *Nemecek et al.*, 2004]. The cusp position and its scale size are affected by the IMF B_y, B_z, dipole tilt angle and the solar wind pressure. The shift of the cusp position by the change of IMF direction is further confirmed by low-altitude statistical study [*Merka et al.*, 2002].

[1]Center for Atmospheric Research, University of Massachusetts Lowell, Lowell, Massachusetts, USA.
[2]State Key Laboratory of Space Weather, Chinese Academy of Sciences, Beijing, China.
[3]Center for Space Physics, Boston University, Boston, Massachusetts, USA.
[4]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[5]Applied Physics Laboratory, Johns Hopkins University, Baltimore, Maryland, USA.
[6]Southwest Research Institute, San Antonio, Texas, USA.
[7]Rutherford Appleton Laboratory, Oxon, UK.
[8]Max-Planck-Institut für Sonnersystemfunsong, Katlenburg-Lindau, Germany.
[9]Centre d'Etude Spatiale des Rayonnements, Toulouse, France.
[10]Space and Atmospheric Physics Group, Imperial College of Science, Technology and Medicine, London, UK.
[11]Mullard Space Science Laboratory, Surrey, UK.

Copyright 2008 by the American Geophysical Union.
0148-0227/08/2006JA012188

[4] The windsock effect due to the deviation of the solar wind velocity from the Sun-Earth line has been indeed observed by the Hawkeye mission [*Boardsen et al.*, 2000]. Further, an explanation of the dawn-dusk displacement of the cusp which was strongly connected to the solar wind azimuthal flow component (which is probably deflected by the large scale heliosphere current sheet/plasma sheet) was suggested by *Lundin et al.* [2001]. The solar wind component flow related displacement shows that there is a "tugging" motion of the cusp location whereby it moves in the direction of the flow. The Earth's magnetosphere will move dawn-ward/dusk-ward when the solar wind has a significant $-Y/+Y$ component. Further, the importance of the solar wind dynamic pressure in the azimuthal and north/south direction as a dynamic driver of the cusp location, and even the whole magnetosphere has been emphasized by *Zong et al.* [2004].

[5] The entry layer is located on magnetospheric field lines just equatorward of the cusp. It is a region of diffusive, turbulent entry of magnetosheath plasma onto closed field lines probably caused by the eddy flow that maps to the low-altitude cusp [*Haerendel et al.*, 1978]. However, the entry layer is basically a region occurring during southward IMF [*Zong et al.*, 2005] since the cusp geometry will be changed by the high-latitude reconnection when the IMF is northward. The cusp reconnection has been observed many times [e.g., *Phan et al.*, 2003]. Magnetosheath-cusp interface when IMF is northward has been discussed before [e.g., *Savin et al.*, 1998; *Lockwood et al.*, 2001; *Lavraud et al.*, 2002; *Taylor et al.*, 2004; *Vontrat-Reberac et al.*, 2003; *Zong et al.*, 2005]; however, the dayside magnetosphere-cusp interface is not fully understood yet, especially during northward IMF with a large B_y component [*Lavraud et al.*, 2004]. The "wavy" nature of the dayside magnetosphere/cusp boundary has also been studied, and the normals and velocities were also found to be consistent with such an oscillatory behavior during a period of highly radial IMF [*Taylor et al.*, 2004]. Motions of the cusp boundaries have been found at speeds up to 60 km/s with a typical speed of 10–20 km/s. These boundaries could represent either global magnetospheric motion including the cusp or expansion/narrowing of the cusp region [*Dunlop et al.*, 2005]. The interface or boundary between the cusp and the magnetosheath appears to be a spatial structure under steady northward IMF conditions [*Lavraud et al.*, 2004, 2005a]. The cusp boundaries are highly dynamic since the cusp is a region where plasma and magnetic pressures are similar, so that a small change in the solar wind dynamic pressure may lead to a large effect in the cusp region, further, the cusp may contain some kind of instability [*Cargill et al.*, 2004]. This is in agreement with previous results by *Newell and Meng* [1994] and *Frey et al.* [2002], who found a much better correlation of the cusp area with the solar wind dynamic pressure than with the magnitude of the IMF B_z.

[6] Under northward IMF, high-latitude reconnection occurs between the magnetosheath and lobe magnetic field lines [*Gosling et al.*, 1991; *Kessel et al.*, 1996]. Because it may occur at both the northern and southern hemispheres simultaneously, *Song and Russell* [1992] proposed the creation of newly closed magnetospheric field lines at the dayside magnetopause when the IMF is strongly oriented northward. This prediction was later supported by case studies [*Le et al.*, 1996; *Onsager et al.*, 2001] and MHD simulations [*Raeder et al.*, 1997]. In this way, inside the cusp, different subregions could be formed which depend on whether the reconnection at both the northern and southern hemispheres occurs simultaneously or not. As pointed out by *Trattner et al.* [2002] that the major cusp structures interpreted as spatial features does not eliminate the importance of pulse reconnection at the magnetopause. In a case study, *Bogdanova et al.* [2005] found three distinct plasma regions inside the cusp. First, injections of magnetosheath-like plasma associated with dawnward and sunward convection suggest Cluster crosses newly reconnected field lines related to the dusk reconnection site. Second, a Stagnant Exterior Cusp (SEC), characterized by nearly isotropic and quasi-stagnant plasma. The last, a region with significant antifield-aligned flows. *Bogdanova et al.* [2005] explained the existence of three different regions inside the cusp by single and dual lobe reconnection geometry. *Onsager et al.* [2001] and *Lavraud et al.* [2005b] particularly focused on the presence of heated magnetosheath electrons streaming in the magnetosheath boundary layer, outside the magnetopause at high latitudes, under northward IMF. On the basis of a case study, they showed that the directionality of the heated electrons may be the signature of whether high-latitude reconnection has already occurred in one or the other, or both, hemispheres. Energetic electron and ion behavior in the high-latitude/cusp region based on the Cluster has been discussed [*Zong et al.*, 2005; *Zhang et al.*, 2005]. Energetic electrons are able to trace magnetic-field-line topology and thus distinguish between open and closed field lines. By using energetic electron observations, early work clearly delineated regions of open and closed magnetic field lines in the high-latitude/cusp region and thus crucially contributed to understanding the cusp dynamics [*Zong et al.*, 2005].

[7] On the other hand, the solar wind plasma penetrating into the magnetosphere may also be explained by a non-reconnection process, known as "Plasma Transport Event" (PTE) [*Lundin et al.*, 2003]. The Flux Transfer Events (FTEs) caused by reconnection process and PTEs may be related process [*Lundin et al.*, 2003]. They might reveal a certain duality in space plasma physics [*Lui*, 2001]. The Kelvin-Helmholtz instability occurring along the flanks of the magnetosphere has long been considered for viscous interaction which can indeed cause a transfer of mass into the magnetotail during times of northward IMF [*Hasegawa et al.*, 2004]. The vortex motion of Kelvin-Helmholtz waves can twist magnetic field strongly to form multiple current layers. The reconnection may occur at those multiple current sheet within a vortex which is responsible for the plasma transport [*Nykyri and Otto*, 2001].

[8] Previous triple cusp event was observed by Cluster during southward IMF [*Zong et al.*, 2004; *Balan et al.*, 2006]. In this paper, we report observations of fourfold cusp event found during northward IMF on 21–22 March 2001. In particular, the interface between the dayside magnetosphere and the cusp will be discussed during an extended northward IMF period. The multiple cusps were surrounded by the dayside magnetosphere. The normal direction and the normal speed of six clear boundaries between the cusp and the dayside magnetosphere together with the crossing order of the Cluster spacecraft indicate that the northern cusp is oscillating with a rough period of 22 min. The clear

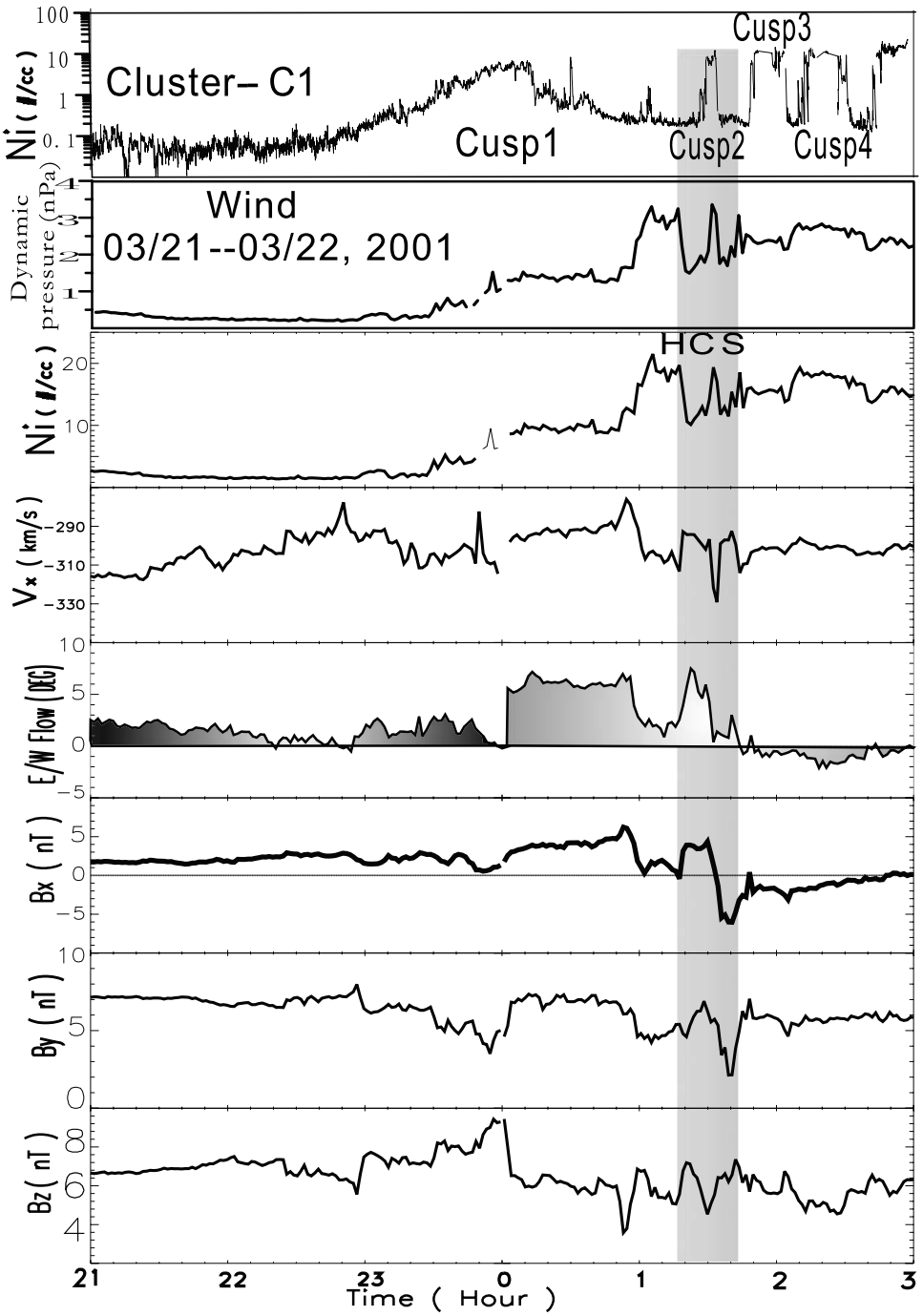

Figure 1. Plasma density from Cluster C1 together with solar wind dynamic pressure, density, velocity V_x component, eastward/westward flow, and the IMF observed by the WIND spacecraft. The Heliospheric Current Sheet (HCS, shaded area), which is identified by the high plasma density and sign change of the IMF B_x, is marked. The time of this figure is shifted according to the solar wind velocity.

transient nature of solar wind plasma penetrating into the magnetosphere and cusp implies dynamical processes which cannot be explained by a steady state physical mechanism. More coordinated observations of multiple satellite measurements for the magnetospheric cusp will help to understand what is the nature of the cusp and what roles do the cusps play in the magnetospheric dynamic process. Understanding the magnetospheric cusp dynamic processes is essential for a thorough understanding of the entire physics of the magnetosphere, and of the interaction or coupling process between the solar wind and any planetary magnetosphere.

2. Cluster Observations

[9] In this section, we focus on the Cluster observations. Since the solar wind and the IMF condition is important for

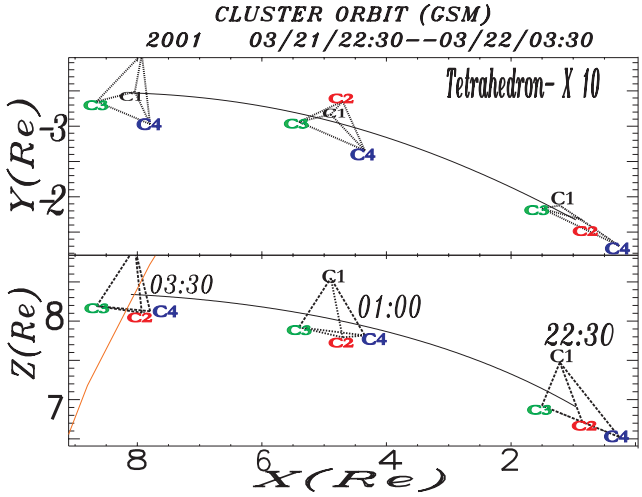

Figure 2. The Cluster trajectory in GSM coordinate system from 2230 UT, 21 March to 0330 UT, 22 March 2001. The scale size of the Cluster tetrahedron has been zoomed in 10 times. The nominal position (unlabeled solid line) of the magnetopause has been scaled according to the model given by *Fairfield* [1971].

the formation of the 4 cusp-like regions, we present the WIND data first.

[10] Figure 1 shows the plasma density from Cluster C1 together with time shifted solar wind and the IMF data observed by the Wind spacecraft located at GSM (−11.7, −183.6, −109.6)R_E. The observations from all four spacecraft are similar so only C1 data are shown here. The time lag between Cluster and Wind is about 6 min with Cluster in advance. During this event, as we can see from Figure 1, the IMF was steady with IMF $B_z > 0$, and IMF B_y is slightly larger or comparable with IMF B_z. Between 0100 and 0330 UT on 22 March 2001, the solar wind speed was 300 km/s and the radial dynamic pressure was around 3 nPa; see Figure 1. A solar wind pressure pulse encountered the Earth at 0058 UT, 22 March 2001, shortly before the second cusp was observed by Cluster while there was a change of solar wind azimuthal flow (shown in Figure 1). The solar wind east/west flow changed from 7 degree to about 2 degree, and the V_x change from −280 km/s to −310 km/s. The changes of solar wind dynamic pressure and azimuthal flow can change the position of the cusp region. We will discuss it in detail later in the discussion part.

[11] The data sets presented in this section were obtained by the RAPID [*Wilken et al.*, 2001], CIS [*Rème et al.*, 1997], PEACE [*Johnstone et al.*, 1997] and FGM [*Balogh et al.*, 1997] instruments on board Cluster. Between 2230 UT, 21 March and 0330 UT, 22 March 2001, the Cluster spacecraft were traveling outbound in the high-latitude region of the northern hemisphere (see Figure 2). Figures 3a–3g give an overview of Cluster measurements between 2230, 21 March 2001 and 0330 UT on 22 March 2001. Four cusp regions can be clearly identified in the high-latitude region with enhanced thermalized sheath plasma ions obtained by CIS instrument (Figure 3a) and electrons obtained by PEACE and RAPID (Figure 3b), plasma ion density (Figure 3f), and depressed magnetic field (Figure 3g) [e.g., *Zong et al.*, 2004]. The fluxes of energetic ions (>30 keV) and electrons (>30 keV) obtained by RAPID instrument are overplotted with plasma ions and electrons in Figures 3a and 3b.

[12] The lower-energy (5 eV to 20 keV) electron spectrogram for 3 different pitch angles (0°, 90°, 180°) obtained by the PEACE/Cluster instrument are given in Figures 3c–3e. Plasma electron measurements show bidirectional (fewer 90° pitch angle electrons), thermalized sheath electrons distribution in all cusp-like regions. There are two population in the dayside magnetosphere: high-energy electrons with higher fluxes in the perpendicular direction and in many places the low-energy low-dense population of electrons with bi-directional fluxes.

[13] All four regions marked as cusp 1–4 can be identified by depressed and/or turbulent magnetic field, high-density plasma and plasma flow significantly slower than the magnetosheath level (velocity for the first cusp crossing is not shown). Also, all cusp regions are characterized by bi-directional distribution of plasma electrons. The later three cusp-like regions are zoomed in in the bottom part of Figure 3. Figures 3h–3l show integral energetic ion (30–4000 keV) and electron (30–500 keV) flux, plasma density, plasma velocity–V_x and V_y components in GSE coordinate system, plasma parallel and perpendicular temperature and the magnitude of the magnetic field from 0100 to 0330 UT, 22 March 2001. The time intervals of those three cusps on 22 March 2001 are from 0130:40 to 0133:32 UT (lasted 2 minutes 52 seconds, the second cusp); from 0152:20 to 0204:30 UT (lasted 12 minutes 10 seconds, the third one) and from 0212:30 to 0225:00 UT (12 minutes 30 seconds, the fourth one). As we can see, the plasma flow V_x component in all cusp regions are significantly slower than the magnetosheath level. As recorded by CIS instrument, the ion temperature was almost isotropic in the cusp region and in the dayside magnetosphere.

[14] The flux of energetic ions stayed almost unchanged when Cluster traveled from the dayside magnetosphere to the cusp regions, whereas the flux of energetic electrons changed dramatically; the flux dropped more than one order of magnitude in the cusp regions. This difference in the ion and electron fluxes is due to the fact that electrons move much faster than ions. Electrons can easily escape along the open field lines in the cusp region.

[15] The later three cusps are further explored in Figure 4. In Figure 4, the integral flux of energetic electrons measured by RAPID instrument and the Y component of the magnetic field obtained by the four spacecraft are shown in the first and second panels. Minimum Variance Analysis (MVA) [*Sonnerup and Cahill*, 1967] has been performed to investigate the six interfaces between the cusp and dayside magnetosphere/trapping region. The normal direction projection on the X-Y plane (ϕ in GSE coordinate system) obtained by all S/Cs are shown in the third panel. All normal directions are well determined with the ratio of intermediate to minimum eigenvalues being above 3. For example, MVA has been performed to investigate the interface between the cusp and dayside magnetosphere from 0128:10 to 0130:40 UT (38 vectors). The normal direction (−0.42, −0.77, −0.48) in GSE coordinate system is well determined with the ratio of intermediate to minimum eigenvalues being above 33.

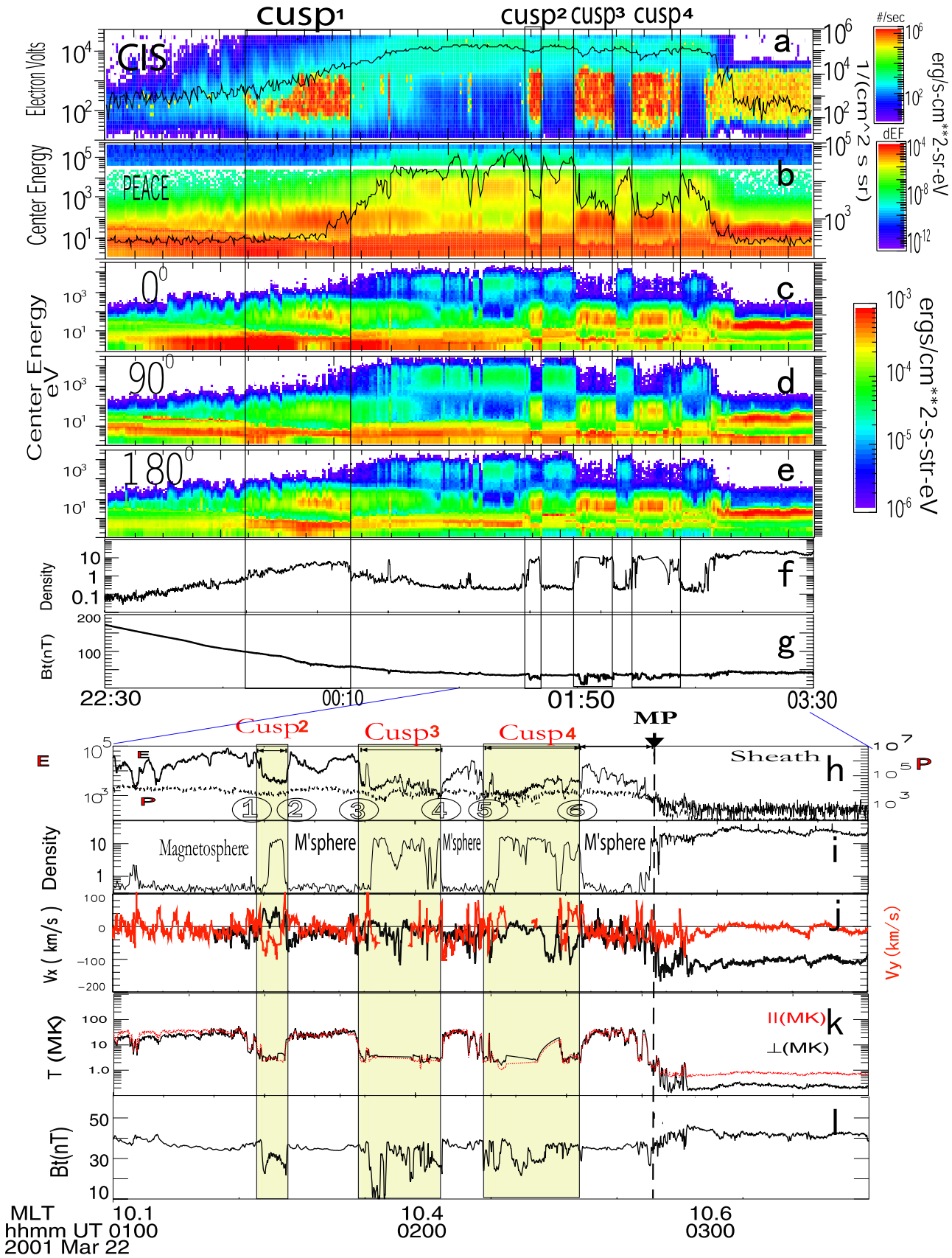
cusp1
cusp2 cusp3 cusp4
CIS
PEACE
Electron Volts
Center Energy
Center Energy eV
Density
Bt(nT)
erg/s-cm**2-sr-eV
ergs/cm**2-s-str-eV
22:30
00:10
01:50
03:30
Cusp2
Cusp3
Cusp4
MP
Sheath
Magnetosphere
M'sphere
Vx (km/s)
Vy (km/s)
T (MK)
II(MK)
⊥(MK)
MLT
hhmm UT 0100
2001 Mar 22
10.1
0200
10.4
0300
10.6

Figure 3

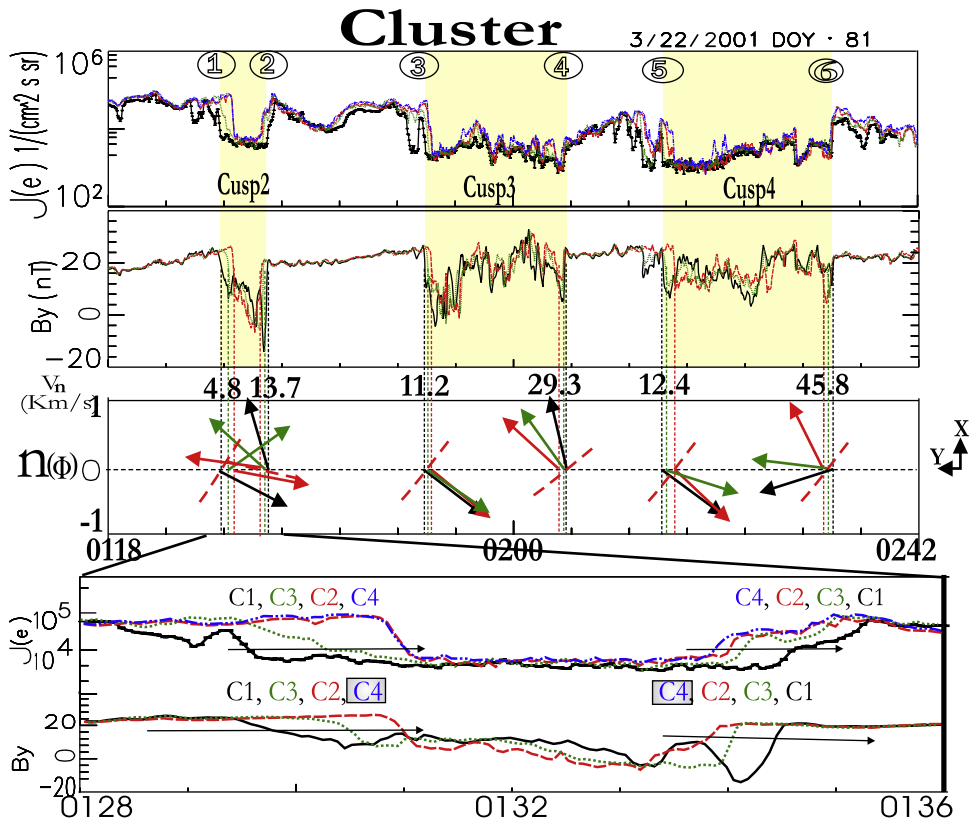

Figure 4. Integral energetic electron flux measured by RAPID instrument, magnetic field B_y component measured by the four Cluster spacecraft during the time period from 0118 to 0242 UT on 22 March 2001. The boundary normals determined by MVA and the boundary moving speed obtained from timing method for all available spacecraft are given in the middle. The number 2 cusp from 0128 to 0136 UT is further expanded to see the spacecraft crossing order more clearly.

[16] Furthermore, by combining the four Cluster spacecraft positions and crossing times at the interfaces, we are able to determine the normal velocity and direction of the discontinuity on the basis of the triangulation method [*Russell et al.*, 1983]. Assuming planar discontinuity and the speed of the discontinuity was constant in time and space over the Cluster separation distance, the equation is simply given by $\mathbf{R_1} \bullet \mathbf{n} = V_n\mathbf{t_1}$. Here V_n is the normal velocity of the discontinuity, $\mathbf{R_1} = (\mathbf{r_{12}}, \mathbf{r_{13}}, \mathbf{r_{14}})$ is a tensor with $\mathbf{r_{ij}}$ being the spacecraft separation vectors and $\mathbf{t_1} = (t_{12}, t_{13}, t_{14})$ consists of the differences between the crossing times of the corresponding spacecraft. The obtained normal speeds for the six interfaces are given in Figure 4 (between the second and third panels). As we can see from the third panel, the wavelike motion can be clearly seen in the ϕ angle, the direction of exiting the cusp at 2, 4, 6 is opposite to the entering direction based on the azimuthal angles.

[17] Although the separation of Cluster spacecraft is only 600 km, the crossing order can be clearly seen when Cluster crossed the interfaces labeled 1 to 6. The interfaces 1 and 2 are enlarged in the bottom panel. The main results are summarized in Table 1. It should be mentioned that the normal velocity v_n at boundary points 2, 4, 6 (exit cusp) is almost three times larger than that at points 1, 3, 5 (enter cusp), the reason of which needs further study. The ratios v_{n2}/v_{n1} v_{n4}/v_{n3} $v_{n6}./v_{n5}$ are 2.9, 2.6, and 3.7, respectively. The angles between the normal directions for the two consecutive cusp boundaries 1 to 6 are shown in Table 1.

3. DMSP Observations

[18] DMSP F12 and F14, traveling from high to low latitude, both crossed a region with magnetosheath like ion and electron precipitations during the Cluster event. The

Figure 3. (top) An overview plot of the observed fourfold cusp by Cluster C1. Figures 3a and 3b show the plasma ion, electron spectrum overplotted with energetic particle fluxes. The electron spectrograms for three different pitch angles (0°, 90°, 180°) obtained by PEACE are shown in Figures 3c–3e. Ion density and the magnitude of the magnetic field are shown in Figures 3f and 3g. I and II mark two distinct plasma subregions inside the first cusp; see the text for details. (bottom) Energetic ion (30–4000 keV) and electron (30–500 keV) flux, plasma moments (density, velocity V_x, V_y components in GSE coordinate system, and temperature), and the magnitude of the magnetic field from 0100 to 0330 UT, 22 March 2001. MP marks the location of the magnetopause. The solid vertical lines mark six boundaries.

Table 1. Cusp-Dayside Magnetosphere Interface Crossing

ID	Time, UT	Region	Speed, km/s	v_o/v_i	α_{io}	Cluster Order	Comment
1	0130:40	into cusp	v_i = 4.8			C1- > C3- > C2- > C4	south and dawnward
2	0133:32	out cusp	v_o = 13.7	2.9	156°	C4- > C2- > C3- > C1	south and duskward
3	0152:20	into cusp	v_i = 11.2			C1- > C3- > C2- > C4	south and dawnward
4	0204:30	out cusp	v_o = 29.3	2.6	127°	C4- > C2- > C3- > C1	south and duskward
5	0212:30	into cusp	v_i = 12.4			C1- > C3- > C2- > C4	north and dawnward
6	0225:00	out cusp	v_o = 45.8	3.7	128°	C4- > C2- > C3- > C1	north and duskward

observations are presented in Figure 5. DMSP F12 and F14 data are time-shifted such that the X axes are the same in Invariant Latitude. As we can see from Figure 5, the features line up to be spatial variation. The difference may be due to the somewhat different magnetic local times of the passages, but may also represent a temporal change over the 30 seconds or so delay between them. Both low-altitude spacecraft observed two large scale regions that are worth noting, in light of the Cluster observations. The cusp is a turbulent region, which often exhibits small scale, <15 km or <2 sec, flux fluctuations in the DMSP ion and electron data. These small scale features are ignored in the present study. In F12 observations, starting at about 0109:04 UT at the most poleward region, the precipitating ion and electron fluxes intensify and the ion energy-time spectrogram exhibits a reverse dispersion that is a typical signature of cusp during northward IMF.

[19] Approximately from 0109:33 to 0110:16 UT, the ion spectrogram exhibits little or no dispersion, although both the ion and electron fluxes are still very intense, typical of cusp precipitations. At a lower latitude, there is a discontinuity at about 0110:16 UT, followed by another region with similarly intense but in higher-energy magnetosheath like ion and electron precipitations between 0110:16 UT and 0110:37 UT. In this region, the ion spectrogram also exhibits little or no dispersion. F14 observed similar features when it encountered the magnetosheath like ion and electron precipitations roughly 30 sec later. Approximately from 0109:33 UT to 0109:52 UT, the ion spectrogram exhibits dispersion at the poleward most region, similar to that observed by F12 30 sec earlier. This is followed by a region with little or no dispersion at lower latitude approximately between 0109:52 UT and 0110:31 UT. Similar to F12 observations, there is a discontinuity roughly at about 0110:32 UT in F14 observations. This is followed by a region containing magnetosheath like ions approximately from 0110:32 UT to 0110:52 UT. In the discontinuity region, the ion fluxes drop significantly from either before or after. In summary, there appears to be two regions with magnetosheath like ions and electrons in the DMSP F12 and F14 observations. The levels of the ion and electron fluxes in both regions are typical for the cusp. The first region exhibits a dispersion, whereas the second one does not.

4. Discussion

4.1. Cold Dense Plasma Sheet Observed by Geotail

[20] The tail plasma sheet becoming cooler and denser during prolonged northward interplanetary magnetic field conditions has been known for more than a decade. However, the mechanism responsible for the formation of cold dense plasma sheet keeps unknown. Two candidate mechanisms have been proposed for the cold solar wind plasma penetration into the hot plasma sheet in the tail. One is the Kelvin-Helmholtz instability which is driven by the velocity shear at the magnetopause [*Fujimoto et al.*, 1996, 1998]. The other is "double lobe reconnection" during northward IMF, i.e., reconnection of lobe field lines and IMF associated with cold and dense sheath plasma at the high-latitude magnetopause in both hemispheres, thereby becoming or forming closed low-latitude boundary layer [*Song and Russell*, 1992].

[21] Several crossings such as those mentioned have been reported on the basis of Cluster observations [*Lockwood et al.*, 2001; *Lavraud et al.*, 2002]. The boundary between the dayside magnetosphere and cusp is a tangential discontinuity separating cusp open field lines from the dayside magnetosphere closed field lines. The interface of the cusp and the dayside magnetosphere during northward IMF could be formed by the newly reconnected flux tubes dispersing into the dayside magnetosphere via the interchange instability [*Song and Russell*, 1992]. Observed bidirectional plasma electron distribution (Figure 3) in the cusp-like region from 0100 to 0330 UT is consistent with the reconnection scenario.

[22] Figure 6 shows the ion spectra for the same time interval as Figure 3. During the time interval from 2230 UT, 21 March 2001 to 0330 UT, 22 March 2001, Geotail satellite was traveling in the magnetotail dusk flank from (−2.4, 15.9, −2.1) R_E to (−7.5, 17.7, −1.8) R_E in GSE coordinate system. The spectra of ions shows that the ions are described by mixing of two population (several hundreds eV and several keV) with some visible dispersions in the cold dense population. These ions always show the quasi-stagnant feature (bottom panel) and plasma density varies from 0.6 to 3 ions/cc (middle panel) for more than three and a half hours. In contrast, the solar wind density at this time was around 15–20 ions/cc, this argues Geotail is indeed inside the magnetosphere rather than the magnetosheath, the cold dense plasma sheet is observed with fluctuation.

[23] When the IMF is northward, a cold dense plasma sheet is often observed [*Baumjohann et al.*, 1989; *Fujimoto et al.*, 1996, 1998; *Terasawa et al.*, 1997]. The magnetosheath plasma near the cusp region is relatively cold compared to the magnetospheric plasma, dense and almost stagnant. When cusp reconnection occurs, the newly reconnected flux tubes tailward of the cusps in both hemispheres sink and contract into the magnetosphere. Subsequently it sweeps around the flank, and is convected tailward. As the plasma is captured and transported to the tail, it is moderately heated near the reconnection site, and the temperature is just below 1 keV [*Song and Russell*, 1992]. The values of

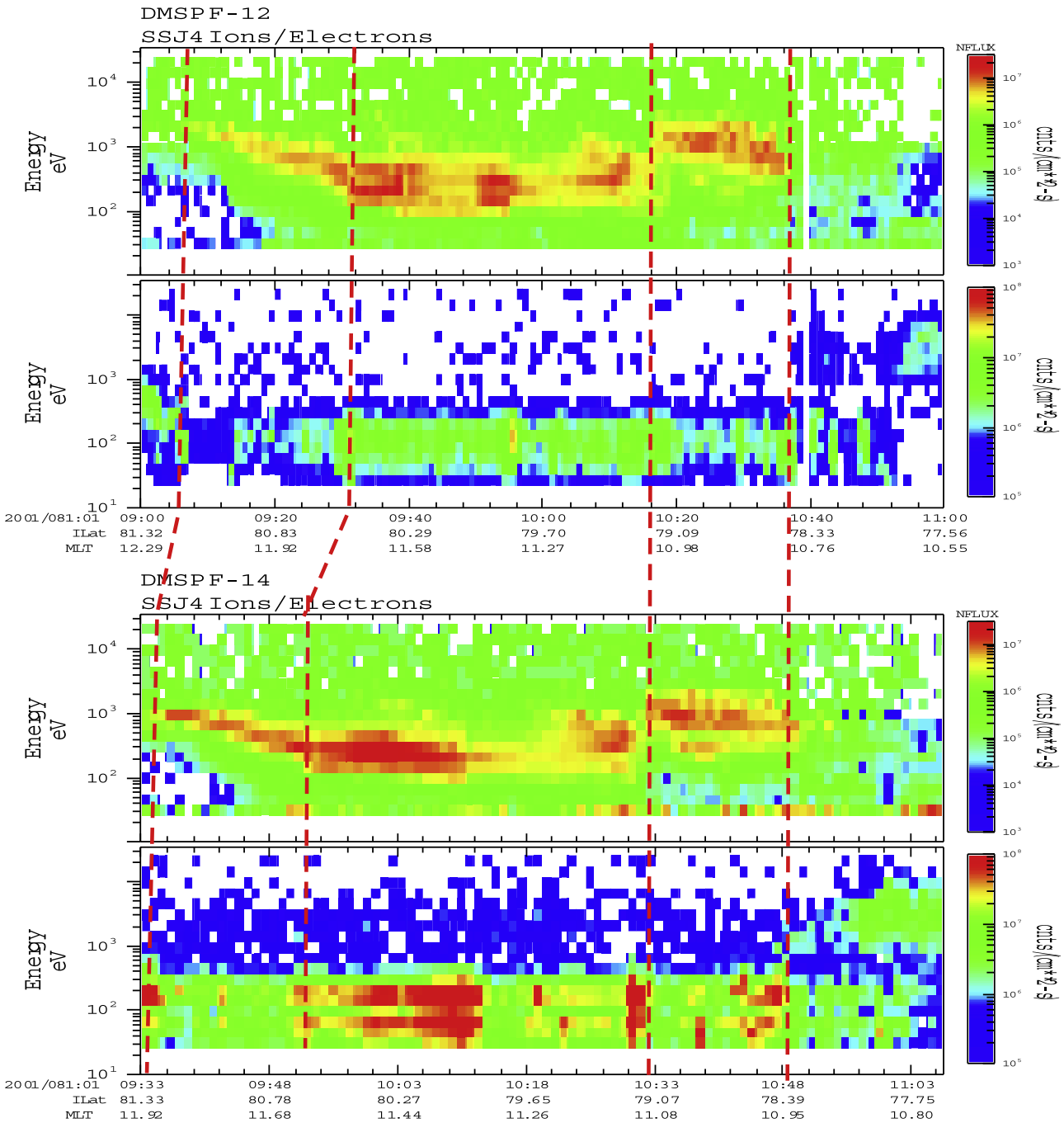

Figure 5. The cusp structures are also observed by two DMSP satellites, F-12 and F-14, on 22 March 2001. Data were taken during the cusp event observed by Cluster spacecraft in the northern hemisphere. The top spectrogram is for ions, and the bottom spectrogram is for electrons. DMSP F14 data are time-shifted so that the X axes for both DMSP F-12 and F-14 data are organized in the same Invariant Latitude.

temperature, density and low flow speed for the captured plasma are in good agreement with Geotail observations in the dusk flank as shown in Figure 6.

[24] It should be noted, the cold dense plasma sheet is also waving. The period is about 20 min. This agrees with the cusp oscillating period (a rough period of 22 min) very well. This is an additional evidence to support the idea that the cold dense plasma sheet observed by Geotail is closely related to the oscillating cusps which are probably formed by high-latitude reconnection during the extended northward IMF period.

4.2. Multiple Cusps and Their Related Phenomena

[25] From 2230 UT, 21 March 2001 to 0300 UT, 22 March 2001 the Cluster spacecraft observed 4 cusp regions. The main cusp (Cusp 1) from 2326 UT, 21 March 2001 to 0013 UT, 22 March 2001 is a normal cusp crossing

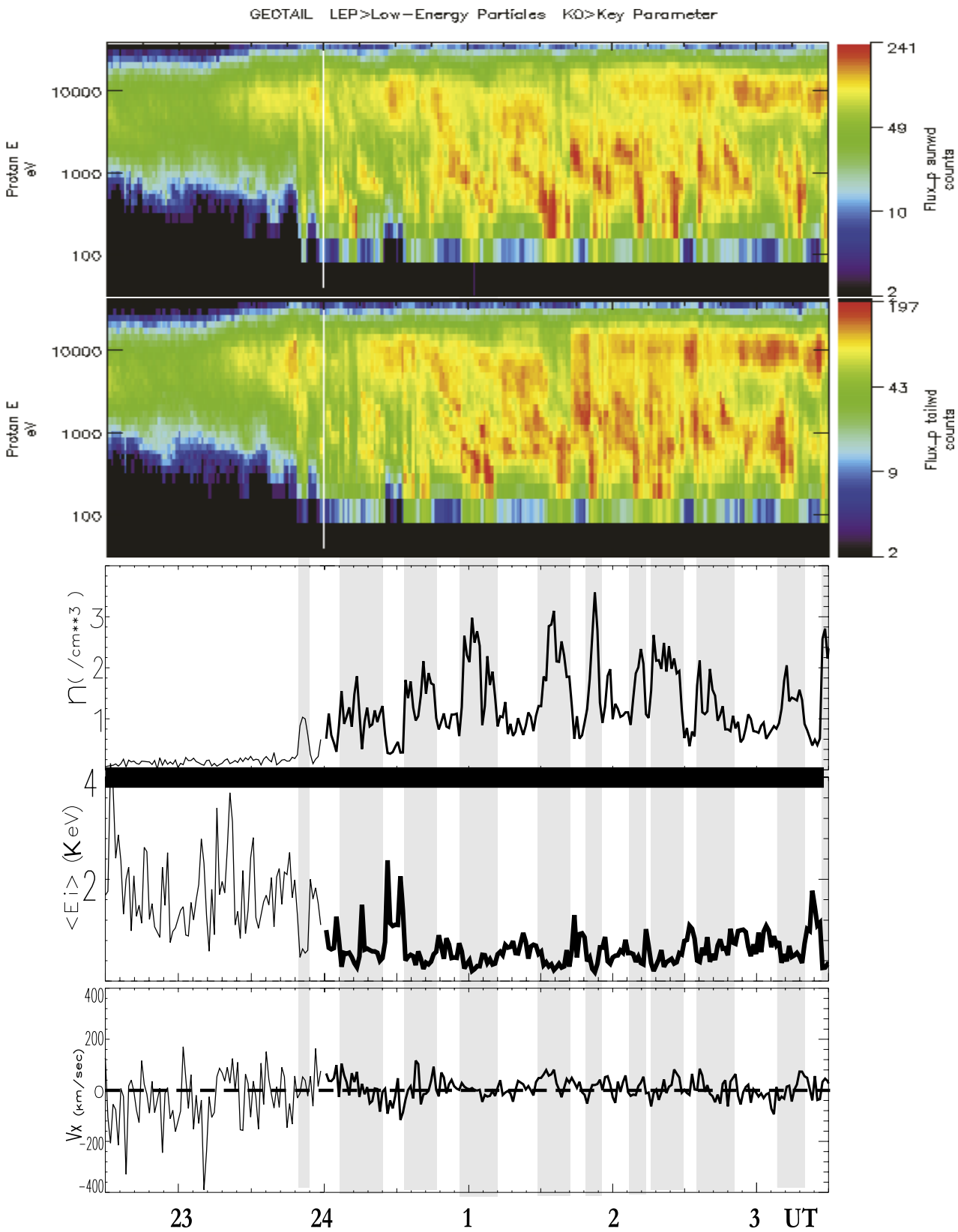

Figure 6. Geotail observations at the duskside tail flank. The top two panels are spectra for sunward and tailward flowing protons, respectively. The bottom three panels show the ion density, the average energy (temperature, in keV), and the ion bulk velocity V_x in km/s. Bursty-like cold-dense plasma are observed (shaded regions).

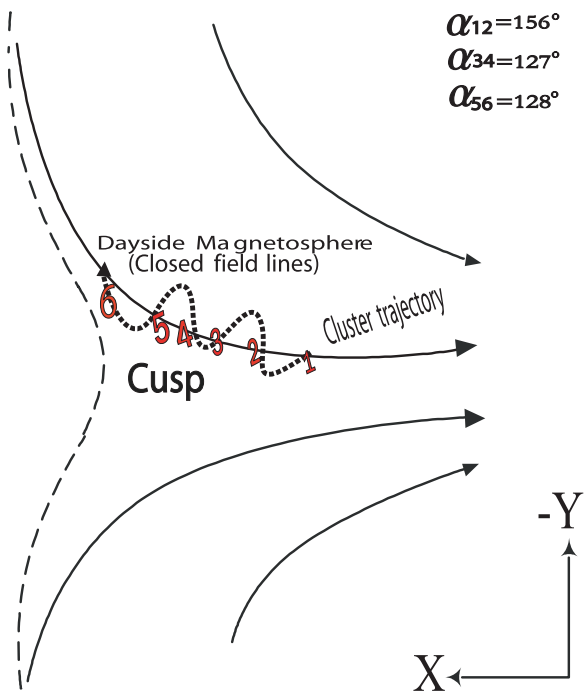

Figure 7. A diagram of the cusp view from the north. The Cluster trajectory relative to the interface of the open and closed field lines is shown. The angles (α_{12}, α_{34}, α_{56}) between the normal directions of the two consecutive cusp boundaries 1 to 6 (Figure 3 and Figure 4) are given.

at relative low altitude; see Figure 2 and Figure 3. The same cusp features observed by two DMSP satellites suggest that these features are spatial, at least for the 30 sec time separation between the two DMSP spacecraft. The entire cusp latitudinal width, stretching nearly 3 degrees, albeit with a small gap (discontinuity), is wider compared to the average cusp latitudinal width of about 2.5 degrees [*Zhou et al.*, 2000]. The cusp signatures observed by the Cluster spacecraft and 2 DMSP satellites are very similar. The first cusp observed by Cluster can perhaps correspond to the high-latitude cusp observed by the DMSP F12 and F14. The relation between the spatial region covered by Cluster in the magnetosphere and that covered by DMSP in the ionosphere can be estimated by assuming the magnetic flux observed by both Cluster and DMSP satellite is the same: $B_{Cluster} \times S_{Cluster} = B_{DMSP} \times S_{DMSP}$, where, B is the observed magnetic field magnitude and S is the sampling area. $S_{DMSP} \approx \frac{S_{Cluster}}{1000}$, so, a small spatial region observed by Cluster may not be visible to DMSP.

[26] After the first cusp, Cluster observed a long stretch of low-level ion fluxes before encountering three more cusps (cusps 2 to 4). As we can see from Figure 3, the plasma signatures (spectrum for both ions and electrons, bi-directional electrons in the cusp region, plasma density, temperature, velocity V_x and depressed total magnetic field) are pretty similar for all four cusps (velocity for the first cusp crossing is not shown). However, the magnetic field is larger and more stable in the first cusp than the following three cusps. That may be caused by the Cluster trajectory. Cluster traveled outbound from lower altitude to the higher altitude. The first cusp is observed in lower altitude so the magnetic field strength is larger and not very turbulent. Cluster crossed the cusp region into the dayside magnetosphere/trapping region. There is a time separation of one and a half hours between the first cusp and the later three cusp-like regions and the magnetic field features are quite different.

[27] The later three cusps, which are located in the lower latitude, are likely caused by oscillation of a single cusp based on the Cluster observation. A schematic diagram in Figure 7 shows the cusp oscillations inferred from the Cluster observations. As shown in Figure 7, the direction changes of the interface between the cusp and dayside magnetosphere are strongly consistent with the wave-like moving cusp. The angles α_{12}, α_{34}, α_{56} between normal vectors at interfaces 1, 3, 5 (enter cusp) and 2, 4, 6 (exit cusp) are 156, 127 and 128 degrees indicating opposite moving directions of the boundaries between the cusp and dayside magnetosphere. The order of the Cluster spacecraft crossing the six interfaces is also consistent with the cusp moving forward and backward. The above facts argue that three consecutive cusps observed by Cluster were indeed a temporal effect.

[28] Cusps 2, 3 and 4 can probably be associated with a reconnection region located poleward of the cusp on the duskside in the northern hemisphere, which is common for northward IMF with a significant B_y component. Since IMF B_y is positive, the reconnection may occur simultaneously in the duskside of the cusp region of the northern hemisphere and in the dawnside region of the southern hemisphere. The plasma in the northern hemisphere is injected to the sunward with significant dawnward direction, which is consistent with the observation (Figure 3j). The higher-energy electron flux (Figure 3h) is also examined and it is found that the electron flux in the cusp region is higher than that in the magnetosheath which serves as an additional evidence for the newly closed field lines in the cusp region otherwise the electrons with speed of 20 R_E/sec would disappear quickly along the open field lines.

[29] The temporal feature can be attributed to cusp boundary movements or possibly instability occurring when the reconnection is continuously occurring. The position of the funnel-shaped cusp which is much larger than the separation of the Cluster spacecraft (about 600 km) strongly depends on the solar wind dynamic pressure or azimuthal flow. The wind sock effect due to the deviation of the solar wind velocity from the Sun-Earth line has been indeed statistically observed by the Hawkeye mission [*Boardsen et al.*, 2000]. As suggested by *Lundin et al.* [2001], the solar wind azimuthal flow component may probably be deflected by the large scale heliosphere current sheet/plasma sheet; see Figure 1. When the solar wind azimuthal flow changed from 7 degree to 2 degree, the cusp was shifted westward and Cluster entered the cusp again and repeated a couple of times [*Zong et al.*, 2004]. As shown in Figure 1, cusp 2 is indeed consistent with the enhanced solar wind component flow and the appearance of the heliospheric current sheet. This shifting in dawn-dusk direction could be the magnetospheric boundary wave triggered by the mentioned solar wind pressure pulse [*Sibeck et al.*, 1998]. It should be mentioned here, the significant enhanced solar wind azimuthal flow with large shear angle to the magnetospheric

lobe field may drive K-H instability in the high-latitude region. This should be a topic for further explore.

5. Conclusions

[30] From 2230 UT, 21 March 2001 to 0300 UT, 22 March 2001 the Cluster spacecraft were outbound in the northern hemisphere over the pole and entered the cusp. A normal cusp region was observed from 2326 UT, 21 March 2001 to 0013 UT, 22 March 2001. Three other cusp-like regions have been observed consecutively from 0130 to 0300 UT, 22 March by all four Cluster spacecraft. All four cusp-like encounters were characterized by turbulent magnetic fields, high-density plasma and plasma flow significantly slower than the magnetosheath level. The cusp-like regions are associated with thermalized electrons. The first encountered cusp is the main cusp (Cusp 1), the other three are temporal effects probably caused by the cusp boundary motion. The normal velocities v_n at boundary interfaces (exit from the cusp) are found to be almost three times larger than that at boundary interfaces (entry into the cusp). The present study provides strong evidences that the newly formed cusp-like region is oscillating in response to the SW changes during northward IMF. The boundary normal, velocity and timing analysis for six clear boundaries of the last 3 cusps obtained by all four spacecraft demonstrates temporal variation; the boundary between the dayside magnetosphere/trapping region and the cusp region was shifted. So the Cluster spacecraft have been observing the same cusp and it appeared as 4 cusp-like regions due to possible magnetospheric oscillations. Multiple cusps observed by Cluster, wavy-like structures observed by Geotail simultaneously during northward IMF suggest the whole magnetosphere is oscillating. The ion dispersion signature together with colder and denser plasma observed by Geotail in the dusk flank of the tail plasma sheet may be related to the high-latitude reconnection observed by Cluster, suggesting that the high-latitude reconnection is possibly responsible for formation of the cold dense plasma sheet.

[31] **Acknowledgments.** We acknowledge the use of the CDAweb database. This work was supported in part by NNSFC 40621003 and 40528005 and by Boston University subcontract GC194770NGA at UMass Lowell by NASA/GSFC grant NNG05GE90G and UAH subcontract 2007-298 at UMass Lowell by NASA grant NNX07AG09G. Simon Wing was supported by NASA grant NNG04GN14G and NSF grant ATM-0538513.

[32] Zuyin Pu thanks Nanan Balan and two other reviewers for their assistance in evaluating this paper.

References

Balan, N., et al. (2006), Cluster observations of a structured magnetospheric cusp, *Ann. Geophys.*, *24*, 1015–1027.

Balogh, A., et al. (1997), The Cluster magnetic field investigation, *Space Sci. Rev.*, *79*, 65–91.

Baumjohann, W., G. Paschmann, and C. A. Cattell (1989), Average plasma properties in the central plasma sheet, *J. Geophys. Res.*, *94*, 6597–6606.

Boardsen, S. A., T. E. Eastman, T. Sotirelis, and J. L. Green (2000), An empirical model of the high-latitude magnetopause, *J. Geophys. Res.*, *105*, 23,193–23,219.

Bogdanova, Y. V., A. Marchaudon, C. J. Owen, M. W. Dunlop, H. U. Frey, J. A. Wild, A. N. Fazakerley, B. Klecker, J. A. Davies, and S. E. Milan (2005), On the formation of the high-altitude stagnant cusp: Cluster observations, *Geophys. Res. Lett.*, *32*, L12101, doi:10.1029/2005GL022813.

Cargill, P. J., M. W. Dunlop, B. Lavraud, R. C. Elphic, D. L. Holland, K. Nykyri, A. Balogh, I. Dandouras, and H. Reme (2004), CLUSTER encounters with the high altitude cusp: Boundary structure and magnetic field depletions, *Ann. Geophys.*, *22*, 1739–1754.

Dunlop, M. W., et al. (2005), Cluster observations of the Cusp: Magnetic structure and dynamics, *Surv. Geophys.*, *26*, 5–55, doi:10.1007/s10712-005-1871-7.

Fairfield, D. H. (1971), Average and unusual locations of the Earth's magnetopause and bow shock, *J. Geophys. Res.*, *76*, 6700–6716.

Frey, H. U., S. B. Mende, T. J. Immel, S. A. Fuselier, E. S. Claflin, J.-C. Grard, and B. Hubert (2002), Proton aurora in the cusp, *J. Geophys. Res.*, *107*(A7), 1091, doi:10.1029/2001JA900161.

Fujimoto, M., A. Nishida, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun (1996), Plasma entry from the flanks of the near-Earth magnetotail: Geotail observations in the dawnside LLBL and the plasma sheet, *J. Geomagn. Geoelectr.*, *48*, 711–727.

Fujimoto, M., T. Terasawa, T. Mukai, Y. Saito, T. Yamamoto, and S. Kokubun (1998), Plasma entry from the flanks of the near-Earth magnetotail: Geotail observations, *J. Geophys. Res.*, *103*(A3), 4391–4408.

Gosling, J. T., D. J. McComas, J. L. Phillips, and S. J. Bame (1991), Geomagnetic activity associated with Earth passage of interplanetary shock disturbance and coronal mass ejections, *J. Geophys. Res.*, *96*, 7831–7839.

Haerendel, G., G. Paschmann, N. Sckopke, H. Rosenbauer, and P. C. Hedgecock (1978), The frontside boundary layer of the magnetopause and the problem of reconnection, *J. Geophys. Res.*, *83*, 3195–3216.

Hasegawa, H., M. Fujimoto, T.-D. Phan, H. Reme, A. Balogh, M. W. Dunlop, C. Hashimoto, and R. TanDokoro (2004), Transport of solar wind into Earth's magnetosphere through rolled-up Kelvin-Helmholtz vortices, *Nature*, *430*, 755–758, doi:10.1038/nature02799.

Johnstone, A. D., et al. (1997), Peace: A plasma electron and current experiment, *Space Sci. Rev.*, *79*, 351–398.

Kessel, R. L., S.-H. Chen, J. L. Green, S. F. Fung, S. A. Boardsen, L. C. Tan, T. E. Eastman, J. D. Craven, and L. A. Frank (1996), Evidence of high-latitude reconnecting during northward IMF: Hawkeye observations, *Geophys. Res. Lett.*, *23*(5), 583–586.

Laakso, H., et al. (1998), Oscillations of magnetospheric boundaries driven by IMF rotations, *Geophys. Res. Lett.*, *25*, 3007–3010.

Lavraud, B., et al. (2002), Cluster observations of the exterior cusp and its surrounding boundaries under northward IMF, *Geophys. Res. Lett.*, *29*(20), 1995, doi:10.1029/2002GL015464.

Lavraud, B., et al. (2004), The exterior cusp and its boundary with the magnetosheath: Cluster multi-event analysis, *Ann. Geophys.*, *22*, 3039–3054.

Lavraud, B., et al. (2005a), Cluster observes the high-altitude cusp region, *Surv. Geophys.*, *26*, 135–175, doi:10.1007/s10712-005-1875-3.

Lavraud, B., A. Fedorov, E. Budnik, M. F. Thomsen, A. Grigoriev, P. J. Cargill, M. W. Dunlop, H. Rme, I. Dandouras, and A. Balogh (2005b), High-altitude cusp flow dependence on IMF orientation: A 3-year Cluster statistical study, *J. Geophys. Res.*, *110*, A02209, doi:10.1029/2004JA010804.

Le, G., C. T. Russell, J. T. Gosling, and M. F. Thomsen (1996), Observations of low-latitude boundary layer for northward interplanetary magnetic field: Implications for cusp reconnection, *J. Geophys. Res.*, *101*, 27,239–27,249.

Lockwood, M., et al. (2001), Coordinated Cluster and ground-based instrument observations of transient changes in the magnetopause boundary layer during an interval of predominantly northward IMF: Relation to reconnection pulses and FTE signatures, *Ann. Geophys.*, *19*, 1613–1640.

Lui, A. (2001), Current controversies in magnetospheric physics, *Rev. Geophys.*, *39*, 535–563.

Lundin, R., B. Aparicio, and M. Yamauchi (2001), On the solar wind flow control of the polar cusp, *J. Geophys. Res.*, *106*, 13,023–13,035.

Lundin, R., et al. (2003), Evidence for impulsive solar wind plasma penetration through the dayside magnetopause, *Ann. Geophys.*, *21*, 457–472.

Merka, J., J. Safrankova, and Z. Nemecek (2002), Cusp-like plasma in the high altitudes: A statistical study of the width and location of the cusp from MAGION-4, *Ann. Geophys.*, *20*, 311–320.

Nemecek, Z., J. Simunek, J. Safrankova, and L. Prech (2004), Spatial and temporal variations of the high-altitude cusp precipitation, *Ann. Geophys.*, *22*, 2441–2450.

Newell, P. T., and C.-I. Meng (1994), Ionospheric projections of magnetospheric regions under low and high solar wind pressure conditions, *J. Geophys. Res.*, *99*(A1), 273–286.

Nykyri, K., and A. Otto (2001), Plasma transport at the magnetospheric boundary due to reconnection in Kelvin-Helmholtz vortices, *Geophys. Res. Lett.*, *28*(18), 3565–3568.

Onsager, T. G., J. D. Scudder, M. Lockwood, and C. T. Russell (2001), Reconnection at the high-latitude magnetopause during northward interplanetary magnetic field conditions, *J. Geophys. Res.*, *106*, 25,467–25,488.

Petrinec, S. M., and C. T. Russell (1993), External and internal influences on the size of dayside terrestrial magnetosphere, *Geophys. Res. Lett.*, *20*, 339–342.

Phan, T., et al. (2003), Simultaneous Cluster and IMAGE observations of cusp reconnection and auroral proton spot for northward IMF, *Geophys. Res. Lett.*, *30*(10), 1509, doi:10.1029/2003GL016885.

Pitout, F., C. P. Escoubet, Y. V. Bogdanova, E. Georgescu, A. N. Fazakerley, and H. Rème (2006), Response of the mid-altitude cusp to rapid rotations of the IMF, *Geophys. Res. Lett.*, *33*, L11107, doi:10.1029/2005GL025460.

Raeder, J., J. Berchem, M. Ashour-Abdalla, L. A. Frank, W. R. Paterson, K. L. Ackerson, S. Kokubun, and J. A. Slavin (1997), Boundary layer formation in the magnetotail: Geotail observations and comparisons with a global MHD simulation, *Geophys. Res. Lett.*, *24*, 951–954.

Rème, H., et al. (1997), The cluster ion spectrometry (CIS) experiment, *Space Sci. Rev.*, *79*, 303–350.

Russell, C. T., M. M. Mellot, E. J. Smith, and J. H. King (1983), Multiple spacecraft observations of interplanetary shocks: four spacecraft determination of the shock normals, *J. Geophys. Res.*, *88*, 4739–4748.

Savin, S. P., et al. (1998), The cusp/magnetosheath interface on May 29, 1996: Interball-1 and polar observations, *Geophys. Res. Lett.*, *25*, 2963–2966.

Sibeck, D. G., R. E. Lopez, and E. C. Roelof (1991), Solar wind control of the magnetopause shape, location, and motion, *J. Geophys. Res.*, *96*, 5489–5495.

Sibeck, D. G., N. L. Borodkova, G. N. Zastenker, S. A. Romanov, and J.-A. Sauvaud (1998), Gross deformation of the dayside magnetopause, *Geophys. Res. Lett.*, *25*, 453–456.

Song, P., and C. T. Russell (1992), Model of the formation of the low-latitude boundary layer for strongly northward interplanetary magnetic field, *J. Geophys. Res.*, *97*(A2), 1411–1420.

Sonnerup, B. U. O., and L. J. Cahill (1967), Magnetopause structure and attitude from Explorer 12 observations, *J. Geophys. Res.*, *72*, 171–183.

Taylor, M. G. G. T., et al. (2004), Cluster observations of a complex high-altitude cusp passage during highly variable IMF, *Ann. Geophys.*, *22*, 3707–3719.

Terasawa, T., et al. (1997), Solar wind control of density and temperature in the near-earh plasma sheet: WIND/GEOTAIL collaboration, *Geophys. Res. Lett.*, *24*, 935–938.

Trattner, K. J., S. A. Fuselier, W. K. Peterson, and C. W. Carlson (2002), Spatial features observed in the cusp under steady solar wind conditions, *J. Geophys. Res.*, *107*(A10), 1288, doi:10.1029/2001JA000262.

Vontrat-Reberac, A., J. M. Bosqued, M. G. G. T. Taylor, B. Lavraud, D. Fontaine, M. W. Dunlop, H. Laakso, N. Cornilleau-Werhlin, P. Canu, and A. Fazakerley (2003), Cluster observations of the high-altitude cusp for northward interplanetary magnetic field: A case study, *J. Geophys. Res.*, *108*(A9), 1346, doi:10.1029/2002JA009717.

Wilken, B., et al. (2001), First results from the rapid imaging energetic particle spectrometer on board Cluster, *Ann. Geophys.*, *19*, 1355–1366.

Wing, S., P. T. Newell, and J. M. Ruohoniemi (2001), Double cusp: Model prediction and observational verification, *J. Geophys. Res.*, *106*, 25,571–25,593.

Zhang, H., T. A. Fritz, Q.-G. Zong, and P. W. Daly (2005), Stagnant exterior cusp region as viewed by energetic electrons and ions: A statistical study using Cluster Research with Adaptive Particle Imaging Detectors (RAPID) data, *J. Geophys. Res.*, *110*, A05211, doi:10.1029/2004JA010562.

Zhou, X. W., C. T. Russell, G. Le, S. A. Fuselier, and J. D. Scudder (2000), Solar wind control of the polar cusp at high altitude, *J. Geophys. Res.*, *105*, 245–251.

Zong, Q.-G., T. A. Fritz, H. Zhang, A. Korth, P. W. Daly, M. W. Dunlop, K.-H. Glassmeier, H. Reme, and A. Balogh (2004), Triple cusps observed by Cluster—Temporal or spatial effect?, *Geophys. Res. Lett.*, *31*, L09810, doi:10.1029/2003GL019128.

Zong, Q.-G., et al. (2005), Energetic electrons as a field line topology tracer in the high latitude boundary/cusp region: Cluster rapid observations, *Surv. Geophys.*, *26*, 213–238, doi:10.1007/s10712-005-1879-z.

A. Balogh, Space and Atmospheric Physics Group, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, UK.

P. W. Daly and A. Korth, Max-Planck-Institut für Sonnersystemfunsong, D-37191 Katlenburg-Lindau, Germany. (daly@linmpi.mpg.de)

M. W. Dunlop, Rutherford Appleton Laboratory, Oxon OX11 0QXUK, UK.

A. N. Fazakerley, Mullard Space Science Laboratory, Surrey RH5 6NT, UK.

R. Frahm and J. D. Winningham, Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228-0510, USA.

T. A. Fritz and H. Zhang, Center for Space Physics, Boston University, Boston, MA 02215, USA. (zong@bu.edu)

M. L. Goldstein and W. Keith, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

H. Rème, Centre d'Etude Spatiale des Rayonnements, 9 Avenue du Colonel Roche, F-31028 Toulouse Cedex 4, France.

S. Wing, Applied Physics Laboratory, Johns Hopkins University, 11100 Johns Hopkins Road, Baltimore, MD 20723, USA.

Q.-G. Zong, Center for Atmospheric Research, University of Massachusetts Lowell, 600 Suffolk Street, Lowell, MA 02215, USA.