Response of the mid-altitude cusp to rapid rotations of the IMF

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[1] On 12 August 2003, the four Cluster spacecraft crossed the mid-altitude cusp one after the other a minute or two apart. Shortly after the cusp crossing, two of the Cluster observed three structures poleward of the cusp that appeared and grew in successive satellite passes. In these structures, high fluxes of low-energy magnetosheath-like ions and electrons are observed. The analysis of particle and magnetic field data reveals that it is the cusp region that moved back and forth over the spacecraft. We show that the cusp reacts extremely fast to rotations of the interplanetary magnetic field (IMF) and that each of the three northward turnings of the IMF is accompanied by a poleward displacement of the cusp. The latitudinal component of the cusp velocity at ~5 R_e altitude is estimated to be of the order of 30 km/s. **Citation:** 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.

1. Introduction

[2] One of the main goals of the Cluster multi-spacecraft mission [*Escoubet et al.*, 2001] is the study of the polar cusp, through which the solar wind plasma has a direct access to the magnetosphere and the ionosphere.

[3] The behavior of the cusp in response to IMF or solar wind changes was widely studied in the past using single spacecraft missions at various altitudes like for instance DMSP at low altitude [*Newell et al.*, 1989], Viking at mid-altitude [*Lundin et al.*, 2001], and Polar at high-altitude [*Palmroth et al.*, 2001] but now, we can take advantage of the multipoint capability of the Cluster mission to study its dynamics in more details. Indeed, when the high-altitude cusp is crossed (nominally in February-March), the configuration is suitable for the study of the cusp in 3D [*Bosqued et al.*, 2001; *Lavraud et al.*, 2002] as the tetrahedral configuration is optimum. The cusp motion can then be monitored in relation to IMF rotations [*Vontrat-Reberac et al.*, 2003; *Taylor et al.*, 2004] or to changes in the azimuthal solar wind flow [*Zong et al.*, 2004] and the velocity of the cusp boundary may be calculated using 3D timing.

[4] On the other hand, cusp dynamics using Cluster at mid-altitude is poorly documented; there are only some rare and recent papers dealing partly with this topic [*Bosqued et al.*, 2005; *Escoubet et al.*, 2006]. As a matter of fact, there are several reasons that make the study of the mid-altitude cusp dynamics very problematic. As the Cluster spacecraft are then near perigee, the crossing is fast and, as another consequence, the configuration is quite elongated, like a string of pearls. Of course this configuration, far from the ideal tetrahedral configuration, makes it impossible to perform 3D analysis. Yet, as we shall see, valuable information on the latitudinal motion of plasma layers can be inferred by studying the timing of successive satellite passes through a given structure or, as it is more often the case for dynamic layers, the timing of the boundary passing through the spacecraft. Incidentally, to be able to perform such a study, one needs the conjunction of several parameters: the spacecraft has to be near the cusp at the very moment when the IMF changes and, since the cusp is less mobile and mid-altitude than at high-altitude [*Palmroth et al.*, 2001] the changes in the IMF have to be large enough to move the cusp significantly so it is observed by several satellites (at least two).

[5] We have found such an event and even more: it is six successive rotations of the IMF which are observed while Cluster sits at the right location, near the cusp region. In this paper, we propose to take advantage of this unique event to study the motion of the cusp in response to IMF variations and to estimate the velocity of the cusp at 5 R_E altitude and to discuss the reactivity of the cusp (and therefore the time scale for the reconnection process at the magnetopause to reorganize) under rapid rotations of the IMF.

2. Observations

[6] On 12 August 2003 around 03:00 UT, the Cluster spacecraft are flying away from perigee, in the northern hemisphere of the dayside magnetosphere. As mentioned above, they fly nearly in a "string of pearls" configuration. The order of flight is very important for the forthcoming analysis; the leading spacecraft is Cluster 1, followed by spacecraft 3, 2, and 4. The time interval we are interested in is 03:40–04:00 UT. Over this time interval, the Cluster spacecraft find themselves near 13 magnetic local time (MLT) and between 74.5° and 76.2° invariant latitude (ILAT). Their altitudes remain close to 5R_E (between 4.87 and 5.04 R_E). We use Cluster data from the Plasma Electron and Current Experiment (PEACE) [*Johnstone et al.*, 1997], the Composition and Distribution Function (CODIF) sensor of the Cluster Ion Spectrometer (CIS) [*Rème et al.*, 2001], and the Flux Gate Magnetometer (FGM) [*Balogh et al.*, 2001].

2.1. Interplanetary Magnetic Field and Solar Wind: ACE

[7] To compare our observations with external conditions, the ACE spacecraft was used to monitor the inter-

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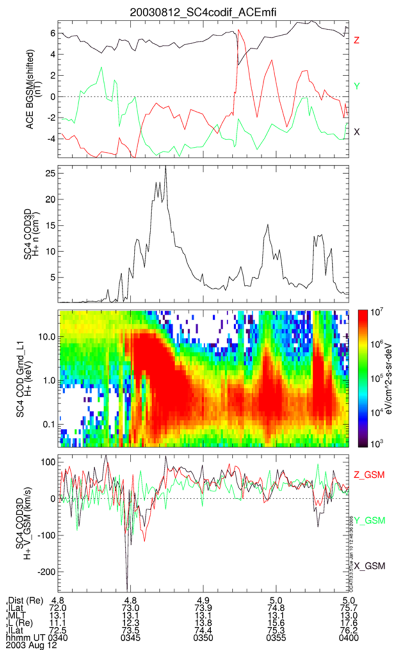

Figure 1. ACE-MFI and CIS-CODIF (spacecraft 4) data with, from top to bottom, the shifted interplanetary magnetic field, the proton density, a proton energy-time spectrogram, and the proton velocity.

planetary magnetic field (MFI instrument) and the solar wind parameters (SWEPAM instrument). On 12 August 2003, the solar wind speed was high, around 650 km/s, and the ion number density around 5 cm^{-3}. The IMF, shown in top panel of Figure 1, was southward ($B_Z \sim -5$ to -2 nT) during the cusp crossing with variations in the Y-component which may explain the disturbed ion dispersion of the cusp (green curve in fourth panel of Figure 1). After the spacecraft have crossed the cusp, the IMF exhibits three rapid changes in the Z-component polarity (red curve in the first panel of Figure 1) corresponding to the structures observed in particle data. Note that in Figure 1, the IMF recorded at ACE has been lagged by 43 minutes in order to account for the propagation time from ACE to Cluster [*Shepherd et al.*, 2002].

2.2. Ion Data: Cluster-CIS

[8] In addition to ACE data (discussed above), Figure 1 shows Cluster CIS-CODIF data from SC4 (the trailing one) between 03:40 and 04:00UT. From top to bottom are displayed the three GSE components of the shifted IMF, proton density, a proton energy-time spectrogram, and the three GSM-components of the proton velocity measured at Cluster.

[9] As the Cluster spacecraft were flying near magnetic noon, they expectedly encountered the northern hemisphere's polar cusp between 03:45 and 03:48 UT. This very short crossing indicates that the cusp is actually crossed on the side or that the cusp was moving because as *Pitout and Escoubet* [2006] and F. Pitout et al. (manuscript in preparation, 2006) have shown, a typical crossing at this altitude lasts on average ∼15 minutes.

[10] Later on, SC4 encounters three structures at ∼03:52, ∼03:54, and ∼03:58 UT. The two last ones have the following properties: high proton density and high energy fluxes (∼10^7 eV/cm^{-2} s sr eV for the two last ones) of low energy ions (200 eV–5k eV). Let us compare the plasma properties within the structures to those in the cusp crossed earlier. First of all, the proton density measured by CIS-CODIF is high in the two last structured at around 10 particles/cm^{-3}. It is not quite as high as in the cusp. The energy spectrogram exhibits high flux of particles having energies between 200 eV and 5 keV, which is very similar to those found in the cusp.

[11] We have to point out that CIS on board SC1 and SC3 further north at higher latitudes do not record those structures. This will be explained later.

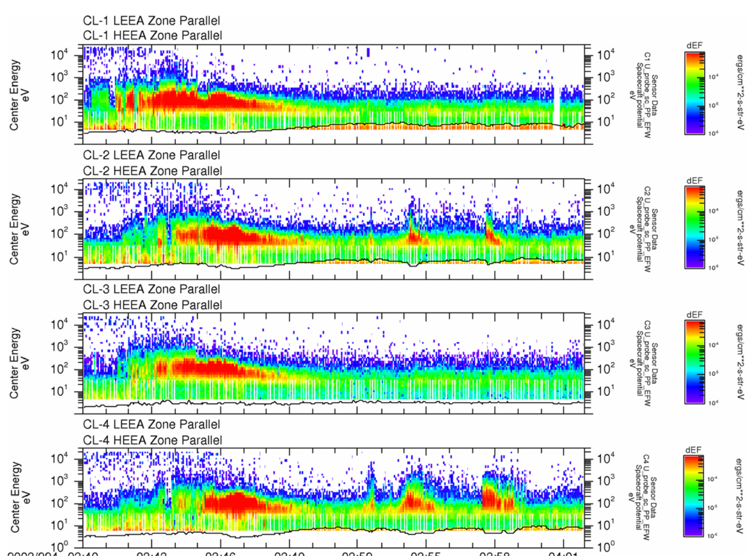

Figure 2. Energy spectrograms of precipitating electrons as measured by the PEACE instrument on board, from top to bottom, spacecraft 1, 2, 3, and 4.

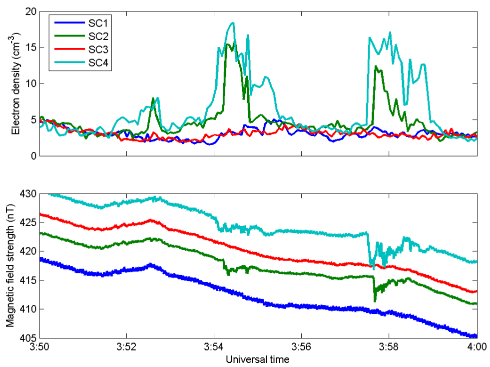

Figure 3. Electron density measured by PEACE and magnetic field strength measured by FGM onboard the four Cluster spacecraft.

2.3. Electron Data: Cluster-PEACE

[12] Figure 2 displays energy-time spectrograms of downgoing electrons recorded by the PEACE instrument on all four spacecraft. The three structures identified in CIS data on SC4 are also present in PEACE data, on both SC2 and SC4 (the two last satellites, SC4 being the trailing one). Their appearances look shorter on SC2. So at first glance, it seems that those structures appear when SC2 passes and grow by the time SC4 arrives.

[13] Electron data also show similarities between the cusp plasma and the plasma within the structures. We have looked at pitch-angle distributions on SC2 and SC4 (not shown). On SC2, the three structures appear as isotropic low energy electron population of ~100eV and below. On SC4, the fluxes are significantly higher but the electron population is basically the same: isotropic and energies around 100eV. These electron populations are typical for the cusp; injected and mirrored magnetosheath electrons coexist on open field lines.

3. Interpretation and Discussion

3.1. Cusp Motion

[14] Before going into the timing, we can first look qualitatively at the order of appearance of the structures in the data. Figure 3 displays the electron density and magnetic field strength at Cluster and it is clear that the structures move poleward and overtake the spacecraft as the trailing satellite (SC4, in cyan) observes the structures first and SC2 (in green) a little later. This is true for all three structures. Then, it appears that SC4 is also the last satellite to observe the structures. This can only be caused by an equatorward motion of those. What initially looked like growing structures in the successive passes of SC2 and 4 are actually a back-and-forth displacement of the cusp region over the spacecraft due to IMF rotations. The fact that both the increase in the density and magnetic field depression are weaker than during the cusp crossing and that SC1 and SC3 do not observe anything suggest that it is the poleward edge of the cusp that is observed.

[15] Timing performed with PEACE data gives velocities of 16.5, 23.9 and 30.4 km/s respectively for the three cusp displacements. Those velocities are worked out in the satellite frame. At 5 Re, the velocity of the satellite (~4.5 km/s) cannot be neglected compared to the typical boundary or plasma velocities [*Lockwood and Smith*, 1994]. The velocities are in fact 21.0, 28.4, and 35.7 km/s respectively in the poleward direction along the satellite track. We apply the same method with time series of the magnitude of the magnetic field recorded by FGM. Although the resolution is much higher, the velocities found are of the same order. Note that the first structure (at ~ 3:52 UT) is very likely due to a cusp displacement as well, even though it is unclear whether it is the cusp that is actually observed by Cluster. This might explain why the velocity found in this case is somewhat lower. We also have to mention that another factor may have helped the cusp to move poleward: the increase in the Z-component of the solar wind velocity from about 0 to +60 km/s (not shown). This occured at 3:22 UT (lagged time), i.e. precisely when the first structure is observed.

[16] Knowing the orbit of the satellites (following one another, at the same altitude, and in the same MLT sector), these velocities give a very good indication of the north-south component of the phase velocity of the cusp. These values are consistent with earlier results by *Lockwood and Smith* [1994] who were able to estimate from mapping of magnetopause and ionospheric boundary motions that the motion of the cusp should have a velocity comparable to the convection velocity, i.e., in the order of 10–50km/s. Our results can also be compared to measurements made at higher altitudes with Cluster: ~20 km/s [*Vontrat-Reberac et al.*, 2003] and 15-50 km/s [*Taylor et al.*, 2004].

3.2. Cusp Poleward Edge Properties and Implications

[17] A first striking feature of the cusp is the sharpness of its poleward edge in particle data as the cusp moves poleward. This is particularly true for the last cusp encounter at ~03:58 UT. For instance, at 1 keV, the ion flux increases by an order of magnitude from one spin to another, i.e., within 4s. Likewise, when the cusp withdraws equatorward, the ion flux decreases also by an order of magnitude. This is unexpected as for southward IMF, the cusp is thought to continuously lead, northward, to the plasma mantle, without such a clear discontinuity, may it be in the plasma or in the field properties. This holds when the plasma convection is due northward. In our case, we cannot neglect the role played by the negative Y-component of the IMF. The cusp plasma flows therefore predominantly westward, i.e., more or less cross track. This westward component of the ion velocity is clearly visible in CODIF data onboard SC4 (green curve in fourth panel of Figure 1). We have then a clear separation between cusp plasma and polar cap plasma. This also explains why SC1 and 4, yet slightly poleward of SC2 and SC4, do not record these structures.

[18] Also, as the cusp moves back equatorward, its poleward edge look very different than when it first moved poleward over the spacecraft. This is clearly visible in both structures. The transitions, as mentioned above, look very sharp while the cusp moves northward and the electron and ion densities increase very fast and peaks at about 10 particles/cm^{-3}. In fact, in our case, this is very likely the transition from a southward IMF cusp to a northward IMF cusp that the spacecraft are recording. Indeed, the last cusp encounter is very interesting from this point of view. In its first part, a "normal" ion dispersion (decreasing energies with increasing latitudes) is visible. It was formed while the IMF was still southward. In the second part (between shortly after 3:58 and 3:59 UT), although short, a hint of

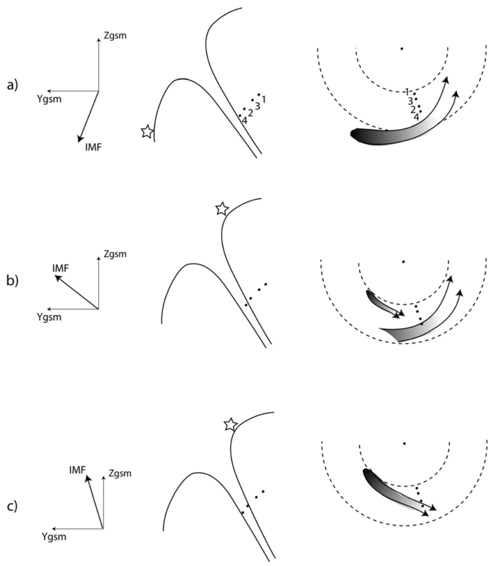

Figure 4. (a–c) For each of the 3 steps, the figure shows from left to right, magnetic field orientation in the (X, Z) plane, schematic of the cusp in the (X, Z) plane with the expected reconnection site (star) and location of the 4 Cluster, and the ionospheric projection of the cusp and the spacecraft. The ionospheric convection flows are shown as black arrows.

reversed dispersion (energies decreases with decreasing latitudes) is clearly visible. This is indicative of lobe reconnection under northward IMF.

3.3. Scenario

[19] To the light of the two previous sections, we are now able to draw a picture of what happened. Figure 4 shows in three stages the effects of the last IMF rotation (~3:58 UT at Cluster) on the cusp location. For each stage, the IMF orientation in the (X, Z) plane (viewed from dusk, the sun being therefore toward the left), the cut of the cusp with the reconnection site, and the ionospheric projection of the satellites, the cusp region and the convection flow. First step, a), the IMF points southward and the cusp sits equatorward of the satellites. Second, b), the cusp starts to move poleward while the IMF starts to rotate from south to north and SC4 records cusp-like particles and enhanced poleward and westward flows while lobe reconnection starts to operate. It has to be noted that lobe reconnection begins within two minutes, the length of time between 2 northward turnings. The cusp moves sufficiently northward to be observed also by SC2 but not by SC3 and SC1. At last, c), sunward flow and particle precipitation due to lobe reconnection (reversed dispersion) reach SC4. When the IMF turns back southward, the cusp moves equatorward as reconnection restarts at the dayside magnetopause (not shown).

4. Conclusion

[20] We have presented a case study of the mid-altitude cusp dynamics using the Cluster spacecraft. Following changes in the IMF orientation, the cusp moved back and forth over the spacecraft a couple of times. From these incursions, we have been able to draw the following conclusions.

[21] 1. The cusp reacts very promptly to rapid changes in the IMF orientations, which means that reconnection at the magnetopause reorganizes very fast (within a couple of minutes).

[22] 2. We have been able to infer the velocity of the cusp poleward boundary. The values found (~30 km/s) are only the north-south components. Thus, this is a lower limit. The Cluster configuration does not allow us to estimate the east-west motion.

[23] 3. The fact that poleward cusp boundary appears sharp when the cusp moves poleward (still under southward IMF or at least, flux tubes originating from dayside reconnection) is very likely due to the effect of IMF By. Newly reconnected flux tubes do not evolve in the same direction as the spacecraft, but cross track.

[24] 4. The last cusp encounter exhibits two ion dispersion (one normal and one reverse) showing, in situ, the transition from a southward IMF to a northward IMF cusp.

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