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Plasmoid in the high latitude boundary/cusp region observed by Cluster

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[1] A plasmoid-like structure without a core magnetic field has been observed by Cluster spacecraft in the high latitude magnetopause region when the interplanetary magnetic field (IMF) is northward and has a dominant duskward component. Bursty electrons and ions are found to be well confined in this plasmoid-like structure. The structure possesses a bipolar signature in the B_N component. The structure is associated with a dramatic change of the plasma flow direction from tailward to dawnward. The plasma density in this structure is slightly enhanced whereas the ion temperature is twice as large as that of the ambient plasma. The plasma parallel temperature is higher than the perpendicular one. The observed structure is different from the traditional Flux Transfer Events (FTEs). The Walén test shows that change of plasma flow velocity are closely associated with change of Alfven velocity which indicates this structure is formed by reconnection process. The observed plasmoid is suggested to be formed by multiple X-line reconnection in the dusk (dawn) side of the stagnant cusp region when the IMF is northward and possesses a dominant positive (negative) B_Y component. **Citation:** Zong, Q.-G., et al. (2005), Plasmoid in the high latitude boundary/cusp region observed by Cluster, *Geophys. Res. Lett.*, *32*, L01101, doi:10.1029/2004GL020960.

1. Introduction

[2] In addition to quasi-steady reconnection, Flux Transfer Events (FTEs), were discovered by *Russell and Elphic* [1978] and *Haerendel et al.* [1978]. It is now widely accepted as a manifestation of transient reconnection although some FTEs could be caused by a transient pressure pulse causing a temporary relocation of the observing spacecraft into the plasma depletion layer and magnetosheath [*Sibeck and Smith*, 1992]. The key defining features of the events are bipolar signature in the boundary normal component of the magnetic field B_N and a rise in the field strength $|B|$ at the center of the structure [*Lockwood et al.*, 2001]. Statistical studies show the FTE occurrence is strongly correlated with a southward interplanetary magnetic field (IMF) [e.g., *Kawano and Russell*, 1996]. However, almost all these studies have addressed around the subsolar magnetopause region. Only a few satellites like HEOS-2, Prognoz-7, Hawkeye and Polar have made in-situ observation in the high-latitude boundary layer regions where the proposed entry for northward IMF takes place. The physical phenomena in the high latitude regions are little known compared to the region around the subsolar point. Recently, FTE-like events have been indeed observed in the high latitude regions by the Cluster spacecraft [*Lockwood et al.*, 2001; *Owen et al.*, 2001; *Zong et al.*, 2003]. *Owen et al.* [2001] focused on the inner structure of FTEs. *Lockwood et al.* [2001] suggests that observed FTEs are formed in the subsolar region, whereas *Zong et al.* [2003] argue that those flux ropes were locally formed in the dusk (dawn) side of the cusp stagnant region by transient component reconnection during northward IMF with a significant positive (negative) B_y component. Only "fossil" FTE [*Lee et al.*, 1993] or a distorted FTE signature [*Crooker*, 1986] will be observed in the high latitude/cusp region if they are formed in the subsolar region.

[3] A transient FTE-like event observed in the high latitude/cusp region will be studied in this paper. We will present detailed observations to suggest the observed structure is a locally produced plasmoid (bipolar B_N but with a weak core field) rather than a traditional FTE or a transient signal caused by boundary motion.

2. Observations

[4] The data used in this study were obtained by the four spacecraft Cluster mission. The energetic particle spectrometer, RAPID, of the Cluster payload features novel detection principles both for ions and electrons [*Wilken et al.*, 1997]. Furthermore, we use magnetometer measurements from the fluxgate magnetometer (FGM) [*Balogh et al.*, 1997] and plasma data from Cluster Ion Spectrometer (CIS) experiment [*Reme et al.*, 1997].

[5] On April 21, 2001, the four Cluster satellites were traveling outbound in the high latitude region of the magnetospheric boundary region (see Figure 1). The spacecraft have separations of ≈600 km. Figure 2 gives an overview of the RAPID, CIS and FGM measurements between 2328 and 2331 UT on April 21, 2001 when Cluster was at GSM (5, −5.2, 7.0) R_E. Figure 2 shows energetic electron (energy range from 30 to 120 keV) and proton (30 to 170 keV) fluxes, the plasma ion density (0.03 to 32 keV), together with the magnetic field in GSM coordinate system. As seen in Figure 2, the enhanced energetic protons as well

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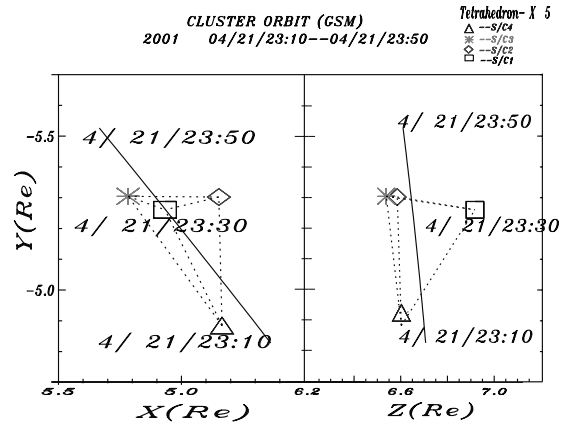

Figure 1. The CLUSTER trajectory from 23:20 to 23:50 UT on April 21, 2001. See color version of this figure in the HTML.

as electrons are well confined in a magnetic structure. The high plasma density indicates Cluster were in the sheath side of the high latitude boundary. This magnetic structure is characterized by a diamagnetic reduction in field strength (panel 8). In this structure, plasma velocity in GSM V_x and V_z component magnitude decreased sharply, whereas Vy showed a significant enhancement – the dawnward plasma flow dominates. The ion parallel velocity clearly changes the sign – from anti-parallel to parallel to the field lines whereas the perpendicular velocity keeps unchanged. The plasma density (panel 2) increases whereas the ion temperature (panel 3) is twice as large as that of the ambient plasma. It can be clearly seen that the plasma parallel temperature is higher than the perpendicular one.

[6] The measured magnetic fields are projected onto a boundary normal coordinate system (*LMN*) in which the N-direction points along the boundary normal (the minimum variance), the L-direction is along the maximum variance direction, the M-direction makes up the right-hand set (Figure 3). The unit vectors **l**, **m**, **n** are given by (0.33, −0.87, −0.37), (0.94, 0.34, 0.03) and (−0.10, 0.36, −0.93). The inflection point of the B_N bipolar signature seen at around 23h29m40s coincided approximately with a depressed total field, indicating that this structure has a weak core field. The peak-to-peak bipolar $\triangle B_N$ is about 22nT. The weak axial field of this structure's center is much less than that in surrounding region (one tenth of the surrounding level). This kind of structure is similar to the plasmoids found in the magnetotail region [e.g., *Zong et al.*, 1997, 2004].

[7] The energetic electron and proton fluxes discussed earlier for all four Cluster satellites on April 21, 2001 are given in Figure 4. C1, C2, C3, and C4 represent the different Cluster spacecraft: Rumba (1), Salsa (2), Samba (3), Tango (4). The arrows indicate the onset times

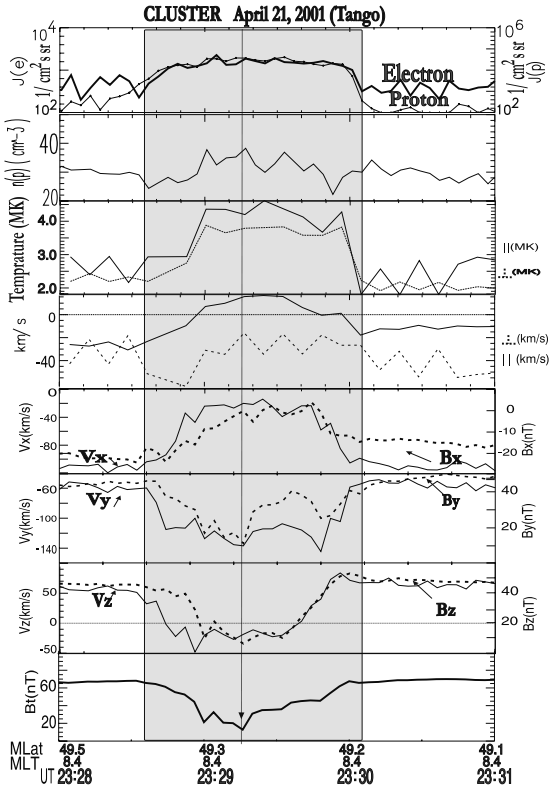

Figure 2. Overview of a plasmoid event between 2328 and 2331 UT on April 21, 2001. From the top the panels show: integral electron and proton fluxes; plasma ion density, ion temperature, ion parallel and perpendicular velocity, ion velocity in GSM system– V_X, V_Y and V_Z (in km/s) and superposed magnetic field B_X, B_Y and B_Z components. The minimum of the total magnetic field intensity is marked. See color version of this figure in the HTML.

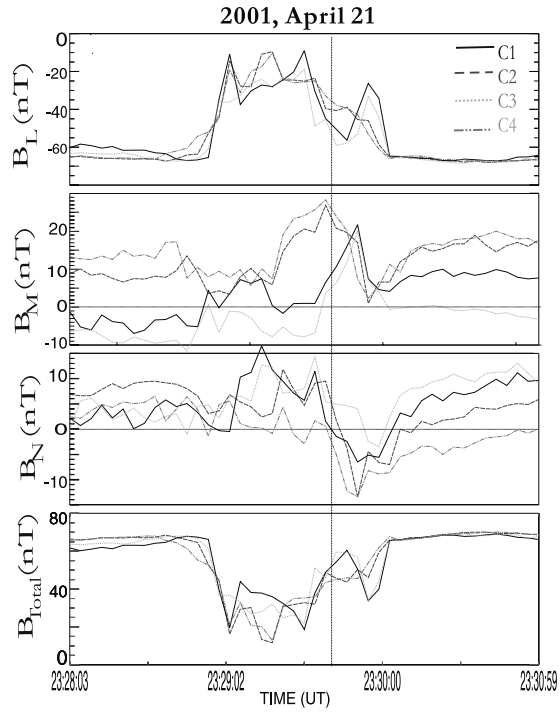

Figure 3. The LMN magnetic field components and field strength observed by the 4 Cluster spacecraft during this period. The decreased field strength and the B_N component showing first positive and negative deflection, which are consistent with a plasmoid structure. See color version of this figure in the HTML.

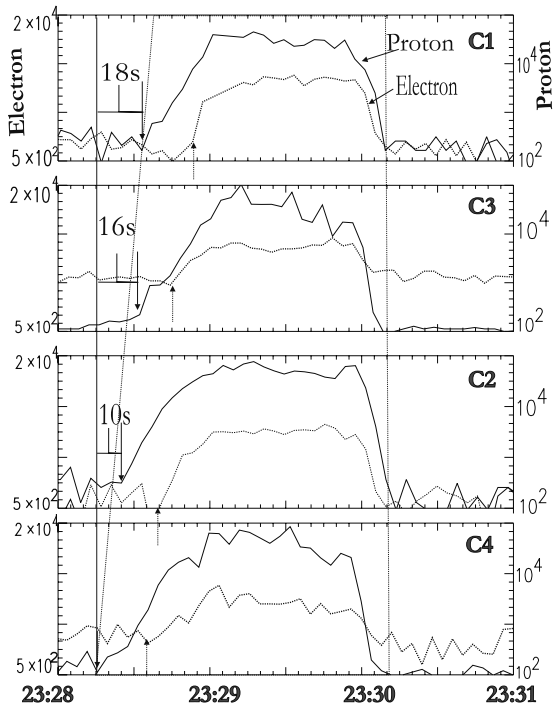

Figure 4. The energetic electron and proton fluxes obtained by RAPID instrument for all four Cluster satellites on April 21, 2001. C1, C2, C3, and C4 represent the different spacecraft: Rumba (1), Salsa (2), Samba (3), Tango (4). The arrows indicate the onset time of the enhancement of energetic electrons and protons. See color version of this figure in the HTML.

of the enhancement of energetic electrons. The onset time of the electron flux detected by four different satellites are slightly different. The maximum time difference between C4 (Tango, the satellite encountering the plasmoid first) and C1 (Rumba, the last spacecraft) is about 18 seconds. Figure 4 demonstrates that the plasmoid was first encountered by spacecraft C4, followed consecutively by spacecraft C2, C3, and C1. The scale size of this plasmoid is estimated to be 1.8 R_E.

3. Interpretation and Discussion

[8] A classical plasmoid with a weak core field (the ratio of the core field to the ambient field is only 0.6) has been observed in the high latitude region when Cluster was traveling outbound on April 21, 2001. Both the plasma V_x and V_z associated with plasmoid decreased (V_x magnitude dropped sharply to around 0) (Figure 2), whereas the V_y showed a significant enhancement. Both the plasma density and temperature are enhanced in this structure. The plasma parallel temperature is higher than the perpendicular one. These facts suggest the observed structure is different from the traditional FTE [e.g., *Lockwood et al.*, 2001] and is not caused by the boundary motion [*Sibeck and Smith*, 1992]. Also, the temperature anisotropy is a good criterion [*Smith and Owen*, 1992] to rule out the magnetopause boundary wave as suggested by *Sibeck and Smith* [1992], since the temperature is anisotropy $T_{parallel} < T_{perpendicular}$ in the plasma depletion layer and magnetosphere. Figure 5 shows that the Walén test for this plasmoid from 23:28:46 to 23:30:30 UT is very well satisfied. The high correlation (C = 0.92) between the change of plasma flow velocity and the change of Alfvén velocity and the slope of the regression (0.927) imply the reconnection occurred. These facts strongly suggest that the observed plasmoid is formed in the stagnant region of the cusp as illustrated in Figure 6.

[9] In contrast to a flux rope formed by the component reconnection, a plasmoid formation without a core field requires anti-parallel merging [e.g., *Crooker*, 1986]. In antiparallel reconnection concept, the initial location of the reconnection is determined by the orientation of the IMF [*Crooker*, 1979]. High latitude reconnection with northward IMF [(2, 9, 4)nT] and a dominant B_y were indeed observed in the interested time interval on April 21, 2001. Including a significant IMF $+B_Y$ ($-B_Y$) in the dusk-side (dawn-side) of the cusp region creates the new topology illustrated in the first panel (marked **1**) of Figure 6. This depicts the dusk-side (dawn-side) of the cusp seen from the sun. Magnetospheric field lines are illustrated below the IMF lines. Because of the presence of a significant IMF $+B_Y$ ($-B_Y$) component, the northward IMF and the magnetospheric field lines in the dusk (dawn) -side cusp region are antiparallel. Multiple x-lines due to tearing mode reconnection could produce a magnetic island at the duskside (dawnside) region of the cusp, and a magnetic flux bulb is formed (**2** in Figure 6). *Crooker* [1986] invoked antiparallel merging to produce a large single island-like structure. The resulting overall field configuration is that of a magnetic island or a plasmoid. If the magnetosheath and magnetospheric fields are not precisely antiparallel, the islands will contain a field component along the island's axis to form a flux rope [*Zong et al.*, 2003]. The motion direction of the plasmoid will be determined either by the magnetic tension on the both reconnection sites of the plasmoid or the side which reconnects first. The magnetic field strength should be larger in the duskside of the plasmoid than that in the cusp side, since the cusp magnetic field is depressed by the Chapman-Ferrero vortex current above the cusp [*Siscoe et al.*, 2002]. Thus, the magnetic tension in the duskside of the plasmoid should be larger than that in the cusp-side of the plasmoid. This newly formed "plasmoid" will move toward the $-$Y direction (Figure 6) if IMF has a significant B_Y. A sketch of the inferred orientation and the motion of

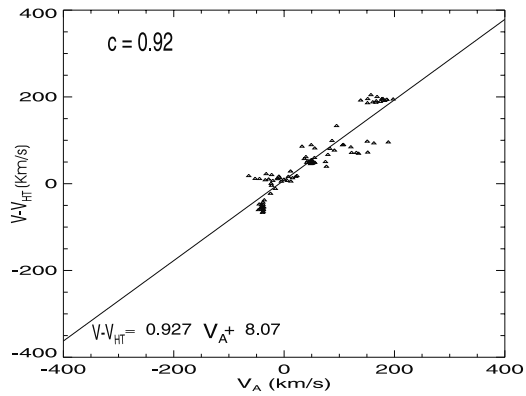

Figure 5. Walén test for the structure showing the relationship between the flow velocity in the deHoffmann-Teller frame and the Alfvén velocity. See color version of this figure in the HTML.

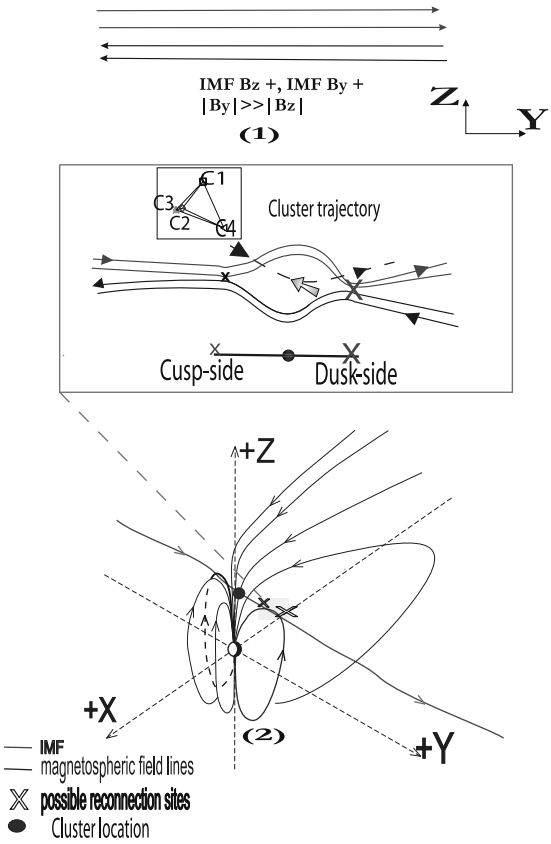

Figure 6. Top: Sketch representation of the magnetospheric field lines are anti-parallel to the IMF. Bottom: A diagram shows how a plasmoid could be generated in the cusp region, see text for detail. See color version of this figure in the HTML.

the observed plasmoid with respect to the four Cluster tetrahedral configuration is also shown in **2** of Figure 6. A plasmoid extended in the YZ plane and with a dominant dawnward velocity will lead the Cluster spacecraft to cross the plasmoid structure. It should be noted that the path of Cluster shown in Figure 6 is caused by the motion of the plasmoid (120 km/s), rather than Cluster satellites (at around 2 km/s). As indicated by the plasma velocity (Figure 2), this plasmoid has a dominant $-V_y$, however, in the trailing edge (from 23:29:40 to 23:30:00), the Vz component is enhanced significantly. This is consistent with the energetic particle (Figure 4) measurements having a clear separation in the beginning, but without a clear separation in the trailing edge as observed by different Cluster S/C.

[10] The main results of this paper can be summarized as:

[11] (1) The energetic electrons and ions embedded in a plasmoid structure have been observed in the high latitude region. Energetic electrons are found to be confined in a smaller spatial extent than energetic ions. This plasmoid is associated with a bipolar B_N component when the IMF has northward Bz and a dominant positive B_Y component.

[12] (2) Both the plasma V_x and V_z associated with plasmoid decreased (V_x magnitude dropped sharply to around 0), whereas the V_y showed a significant enhancement. The plasma density in this structure is slightly enhanced whereas the ion temperature is twice as large as that of the ambient plasma. The plasma parallel temperature is higher than the perpendicular one. These facts suggest the observed structure is different from the traditional FTE.

[13] (3) The observed plasmoid is probably formed by multiple X-line reconnection in the dusk (dawn) side of the stagnant cusp region when the IMF is northward and possesses a dominant positive (negative) B_Y component.

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