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Local field-aligned currents in the magnetotail and ionosphere as observed by a Cluster, Double Star, and MIRACLE conjunction

T. Takada,[1] R. Nakamura,[2] L. Juusola,[3] O. Amm,[3] W. Baumjohann,[2] M. Volwerk,[2] A. Matsuoka,[1] B. Klecker,[4] K. Snekvik,[5] C. J. Owen,[6] A. N. Fazakerley,[6] H. U. Frey,[7] H. Rème,[8] E. A. Lucek,[9] and C. Carr[9]

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[1] During a fortuitous conjunction event observed by Cluster, Double Star TC1, and Magnetometers–Ionospheric Radars–All-Sky Cameras Large Experiment (MIRACLE) magnetometer stations at almost the same local time, crossings of the plasma sheet boundary layer (PSBL) are observed with a 45–50 s delay between the two spacecraft located approximately 6 R_E apart in X. Taking into account the different polarity of B_Y, Cluster curlometer current density, and the curl of the equivalent current on the ground, the associated current system resembles that of a bubble model, i.e., the propagation of a bursty bulk flow (BBF) with field-aligned currents (FACs) on each side of the flow. The presence of such local FACs associated with BBFs is supported by the time delays of PSBL crossings, corresponding weak auroral brightening, and enhancement of the ionospheric equivalent current pattern. The Cluster observation also shows different signatures between inbound and outbound crossings, i.e., electron beam direction. Such differences are considered to be caused by the relative location of the observation point from the beam ejection region, such as reconnection, and may suggest that the beam ejection region is approaching during the PSBL crossing.

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1. Introduction

[2] Bursty bulk flows (BBFs) play an active role in magnetospheric substorms [cf. *Baker et al.*, 1996; *Angelopoulos et al.*, 1999; *Baumjohann*, 2002]. One of the important aspects of this BBF activity is the connection of a BBF to the ionosphere through field-aligned currents (FACs). Theoretical work suggests that on the dawnside of the flow burst there is an earthward FAC and a tailward FAC on the duskside [*Pontius and Wolf*, 1990; *Chen and Wolf*, 1993, 1999; *Ji and Wolf*, 2003], and observations of these FACs have been reported [e.g., *Sergeev et al.*, 1996; *Nakamura et al.*, 2001a, 2001b; *Snekvik et al.*, 2007].

[3] Signatures of flow bursts are also observed in the plasma sheet boundary layer (PSBL), where a plasma jet is a rather collimated beam such as the earthward ion beam at the outer edge and counterstreaming ions at inner edge [*Onsager et al.*, 1991; *Nakamura et al.*, 1992]. Since such PSBL beams are observed by a single spacecraft in a short time period [*Grigorenko et al.*, 2002], the beam is called a "beamlet" [*Ashour-Abdalla et al.*, 1991]. *Grigorenko et al.* [2007] investigated the Cluster multispacecraft beamlet events in the PSBL and suggest that the beamlet layers look like a kink shape in the *X-Y* plane and are associated with a fast flapping in the *Y-Z* direction, which might be caused by the fire-hose instability [e.g., *Takada et al.*, 2005a].

[4] The ionospheric signatures associated with BBFs have been observed in several studies [e.g., *Angelopoulos et al.*, 1999; *Sergeev et al.*, 2000, 2004a; *Nakamura et al.*, 2001a, 2001b, 2004; *Amm and Kauristie*, 2002; *Grocott et al.*, 2004; *Amm et al.*, 2006]. Recently, the corresponding signatures of BBFs in the magnetosphere and ionosphere have been observed during Cluster and Magnetometers–Ionospheric Radars–All-Sky Cameras Large Experiment (MIRACLE) conjunction [*Nakamura et al.*, 2005]. However, the complete structure of a BBF and its connection to the ionosphere are still unknown due to the lack of large-scale multipoint observations in the magnetotail.

[5] In this study, a fortuitous observation of Cluster, Double Star Program (DSP) TC1, and MIRACLE conjunction is examined in detail, and the whole structure of a local

[1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan.
[2]Space Research Institute, Austrian Academy of Sciences, Graz, Austria.
[3]Finnish Meteorological Institute, Helsinki, Finland.
[4]Max-Planck-Institut für extraterrestrische Physik, Garching, Germany.
[5]Department of Physics and Technology, University of Bergen, Bergen, Norway.
[6]Mullard Space Science Laboratory, University College London, Dorking, UK.
[7]Space Sciences Laboratory, University of California, Berkeley, USA.
[8]CESR, CNRS, Toulouse, France.
[9]Blackett Laboratory, Imperial College, London, UK.

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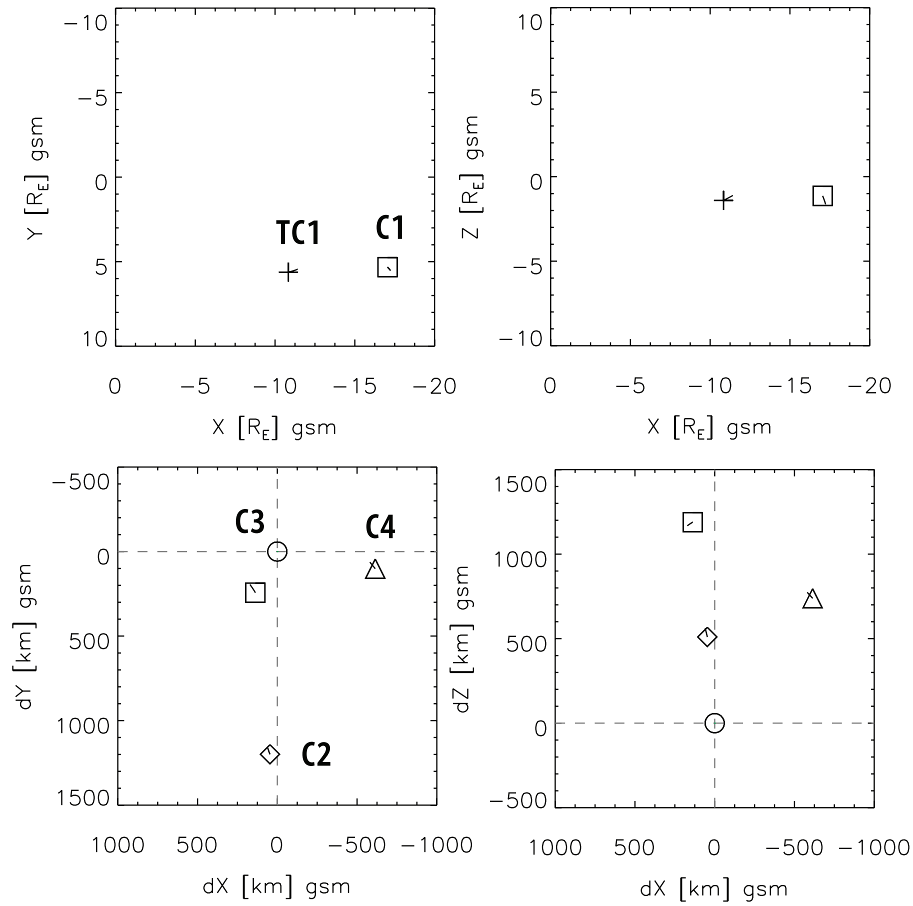

Figure 1. (top) Locations of the spacecraft on 26 September 2004 in GSM *X-Y* and *X-Z* planes. (bottom) Relative separations of the Cluster spacecraft in the *X-Y* and *X-Z* planes.

FAC system associated with a BBF is discussed. We use data obtained by the Fluxgate Magnetometer (FGM) instrument on Cluster [*Balogh et al.*, 2001]; on TC1 [*Carr et al.*, 2005], the Composition and Distribution Function analyzer (CODIF) and Hot Ion Analyzer (HIA) of the Cluster Ion Spectrometry experiment (CIS) [*Rème et al.*, 2001]; and the Plasma Electron and Current Experiment (PEACE) [*Johnstone et al.*, 1997] on board Cluster. The aurora images are provided every 2 min by the Far Ultraviolet imager (FUV) wideband imaging camera (WIC) on board the IMAGE spacecraft [*Mende et al.*, 2000].

2. Observation

[6] On 26 September 2004, Cluster and TC1 were located in the magnetotail at (−17.1, 5.3, −1.1) R_E and (−10.8, 5.6, −1.4) R_E in GSM coordinate, respectively (see Figure 1). Both spacecraft are located close to each other in the *Y-Z* plane. The separation of four Cluster spacecraft is roughly 850−1400 km. The footprints of both spacecraft are close to the MIRACLE network.

[7] Figure 2 shows an overview of the event observed by Cluster 1 (C1) and TC1. Since the spacecraft separation is small, other Cluster spacecraft show trends similar to C1. C1 and TC1 are mainly in the southern magnetotail lobe region. At around 1930 UT, TC1 observes the successive dipolarizations while C1 observes the PSBL crossings. The PSBL is referred in this study as a region between the plasma sheet and the lobe, satisfying the condition of moderate (0.05−0.3) plasma β, the ratio between the thermal pressure and the magnetic pressure [*Baumjohann et al.*, 1988]. The observations by both the spacecraft are typical substorm signatures which are identified as a small substorm by the IMAGE WIC shown in later. Afterward, there are a few PSBL crossings observed by both or either of the spacecraft. These crossings are also accompanied by weak auroral brightening. The crossing around 1955 UT (shaded area) shows the clearest B_Y signature, both at Cluster and TC1, and is associated with auroral brightening. Since the spacecraft are in the same hemisphere and on the duskside, opposite polarity of B_Y between the two spacecraft might suggest a different direction of FAC. Enhancement in ion velocity was also observed and identified as an earthward stream at the PSBL. In order to assess the local current closure, we focus on this interval further in this study.

[8] The four Cluster spacecraft and TC1 observations are shown in Figure 3. The PSBL crossings are identified by β enhancement (not shown) from 1952:50 to 1953:50 UT at Cluster and from 1953:50 to 1954:30 UT at TC1, respectively. During each PSBL crossing, the magnetic field variations are similar: a decrease of $|B_X|$, a large variation of B_Y and a bipolar B_Z except for the B_Y polarity between

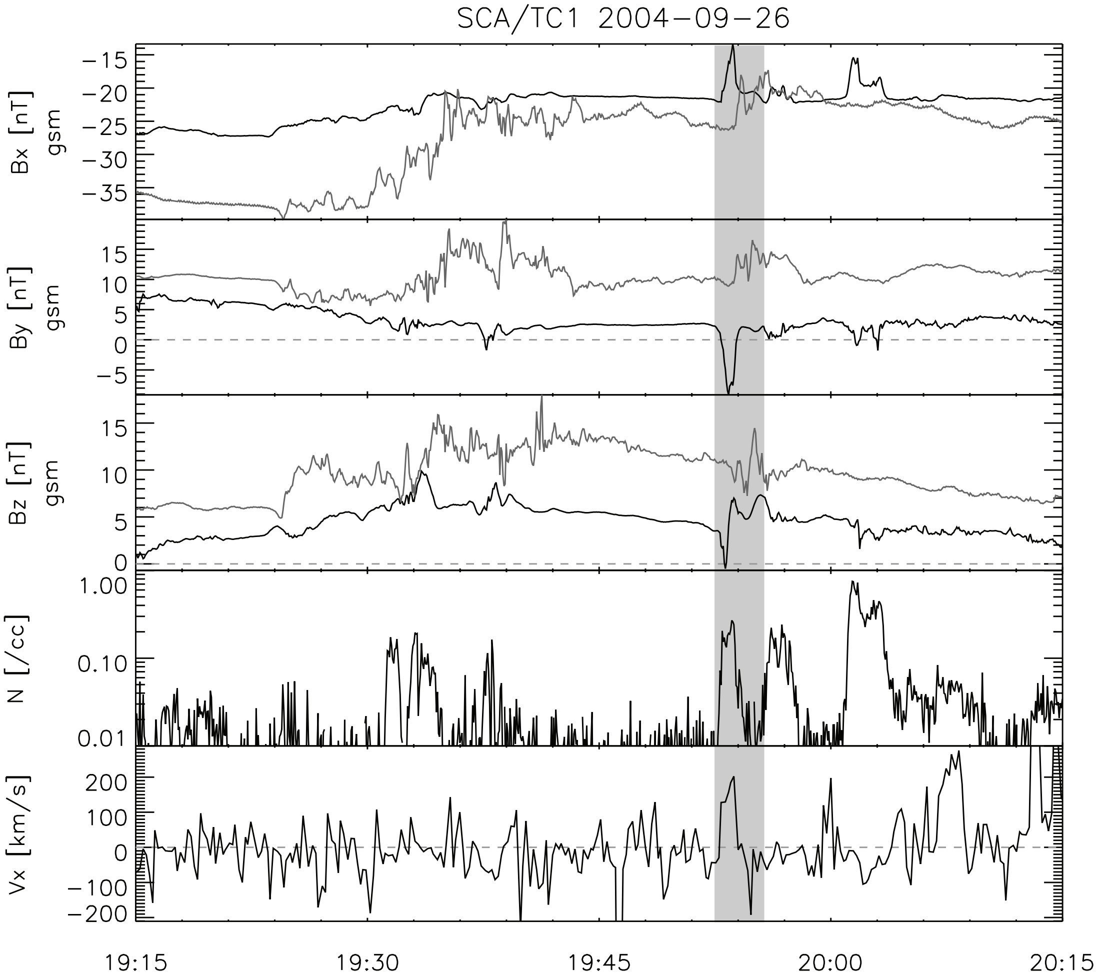

Figure 2. Cluster C1 (black) and TC1 (gray) observations on 26 September 2004 of three components of magnetic field, proton density and *X* component of ion velocity. Gray shaded interval is expanded in Figure 3.

Cluster and TC1. TC1 continues to observe the second crossing after 1954:30 UT. However, in this study we focus only on the first one. The estimated current density by the Cluster curlometer technique [*Chanteur*, 1998] shows the antiparallel direction of FAC in the Southern Hemisphere, i.e., the earthward FAC at Cluster. Note that the parallel current density is dominant at the edges of the inbound (spacecraft motion from the lobe to the plasma sheet) and outbound (from the plasma sheet to the lobe) directions, indicating that the FAC layer is located exactly on the outward edge of the PSBL. In this situation the earthward FAC is equivalent to the negative variation of B_Y at Cluster. Thus, the positive variation of B_Y at TC1 is considered to be due to a tailward directed FAC. These FACs are considered to be maintained by Alfvén waves [*Takada et al.*, 2005b]. In this event, we confirmed that the $\Delta E/\Delta B$ is approximately the local Alfvén velocity, $V_A \sim 1000$ km/s. Although during the PSBL crossing the magnetic pressure decreases and plasma pressure increases, the total pressure enhances, which indicates a compression of the magnetotail by a moving object inside the plasma sheet, such as a traveling compression region (TCR) [cf. *Slavin et al.*, 2005]. If we look carefully into the differences among the spacecraft, we find that the pressure enhancements are larger inside the plasma sheet than outside ($P_{C3} < P_{C4} < P_{C1}$).

[9] Assuming a moving object, we first estimate the propagation speed between Cluster and TC1 using the time delay 45–50 s of PSBL crossing. Taking into account the spacecraft separation between C1 and TC1, $\boldsymbol{D}$ = (−38000, −400, −1500) km, the propagation speed is roughly estimated as 700–850 km/s earthward. This speed is in the range of BBFs, which is originally defined as an earthward fast bulk flows in the central plasma sheet [*Angelopoulos et al.*, 1992]. Thus the PSBL crossings can be interpreted as being due to the propagation of a BBF in the central plasma sheet. Using Cluster multispacecraft timing analysis [*Harvey*, 1998], the propagation speeds of the boundary are estimated as 121 km/s with $\boldsymbol{n}$ = (0.27, 0.66, −0.70) at the inbound crossing and 122 km/s with $\boldsymbol{n}$ = (0.12, 0.59, 0.80) at the outbound. Each boundary crossing is identified as a timing of a minimum theta angle, θ_B (an elevation angle from the *X-Y* plane) and total field, B_T, respectively. *Grigorenko et al.* [2007] reported that a kink-type movement of the boundary layer in the *Y-Z* plane is commonly observed in the PSBL beamlet events. However, when we assume the *Y* propagation such as a plasma sheet oscillation

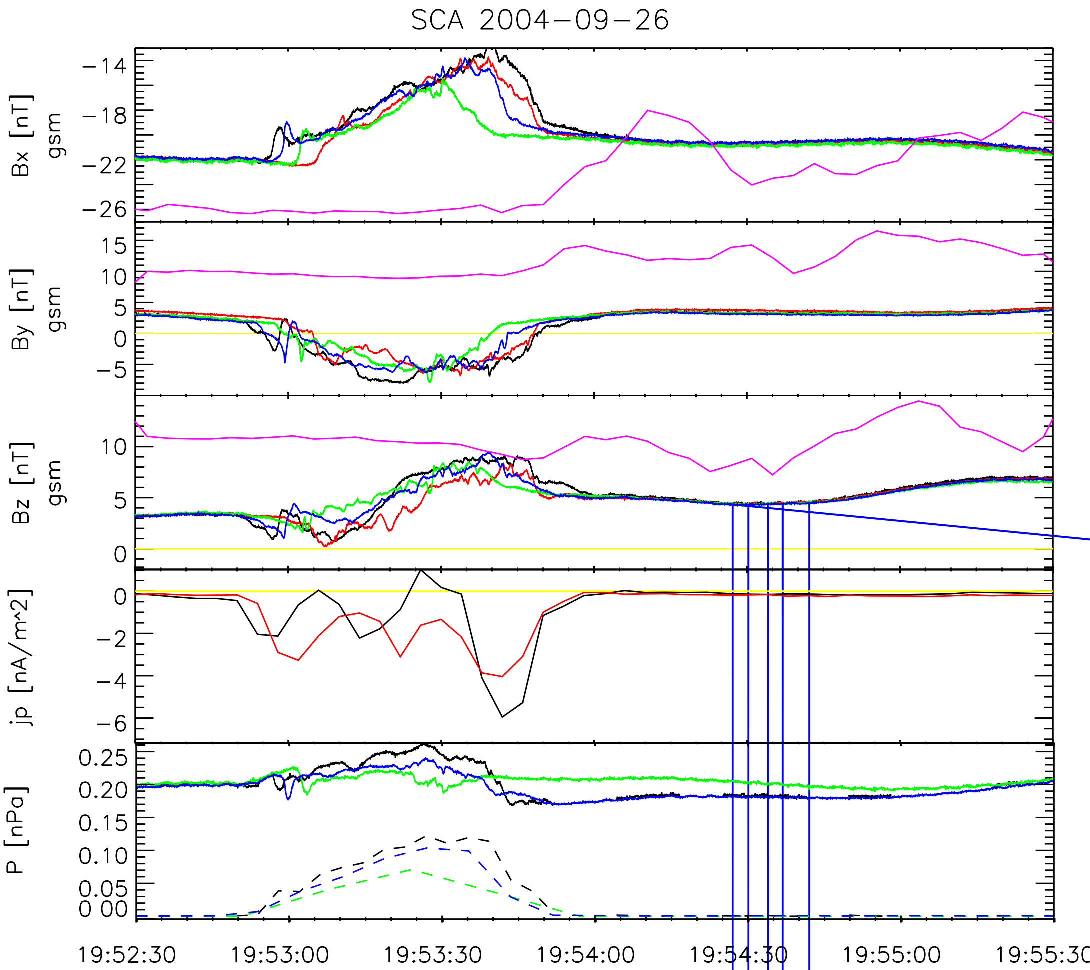

Figure 3. Cluster and TC1 observations on 26 September 2004. From top to bottom, three components of magnetic fields, the current density of parallel (black) and perpendicular (red) components, and total (solid) and thermal (dashed) pressure are shown by black (C1), red (C2), green (C3), blue (C4), and pink (TC1).

[e.g., *Runov et al.*, 2003; *Sergeev et al.*, 2004b, 2006], the delay time between Cluster and TC1 are estimated for 172 s and 111 s at the inbound and outbound crossings, respectively, assuming the propagation of a long straight object and spacecraft separation in *X-Y* plane. This assumption is based on the fact that the azimuthal propagation of plasma sheet oscillation is extended roughly more than 5 R_E along *X* direction [*Zhang et al.*, 2005]. Since these delays are almost three times as long as the observed time delay of 45–50 s, the observed PSBL entry by TC1 cannot be a simple *Y* propagation of an *X* elongated wavefront from Cluster to TC1. On the other hand, the relatively small propagation velocity in *X* compared to that in the *Y* direction at Cluster suggests that the PSBL entries cannot be a simple entry of a fast earthward moving plasma bulge such as expected for TCR/flux rope cases [*Slavin et al.*, 2003]. One plausible interpretation would be that the observed time difference of PSBL entries are caused by kink-like disturbances induced by BBF itself [*Sergeev et al.*, 2006] and therefore reflect more the timing of the BBF velocity than the propagation velocity of the disturbance.

[10] In the PSBL, the ions display a unidirectional earthward beam in the outer edge and a counterstreaming beam in the inner edge (not shown). These field-aligned beams (FABs) are typical PSBL signatures, which are explained by time of flight and convection effect [*Onsager et al.*, 1991]. Conversely, the electron observation shows interesting features. Although all the spacecraft show the same features, the pitch angle distribution of C1 and C4 are displayed here for the reference. As expected, the earthward electron beam is observed at the inbound crossing for a shorter time than the earthward protons, and the bistreaming electrons are observed during most crossings, shown in Figure 4 (left and middle). However, the tailward electron beam is observed at the outbound crossing, shown in Figure 4 (right). This type of beam is often observed associated with the Hall current system in a reconnection site [e.g., *Nagai et al.*, 2001].

[11] In order to examine the connections of FAC in the ionosphere, the equivalent current and its curl are estimated every 10 s from the MIRACLE magnetometers [*Syrjäsuo et al.*, 1998]. The detailed description of 2-D upward continuation technique is referred to *Amm and Viljanen*

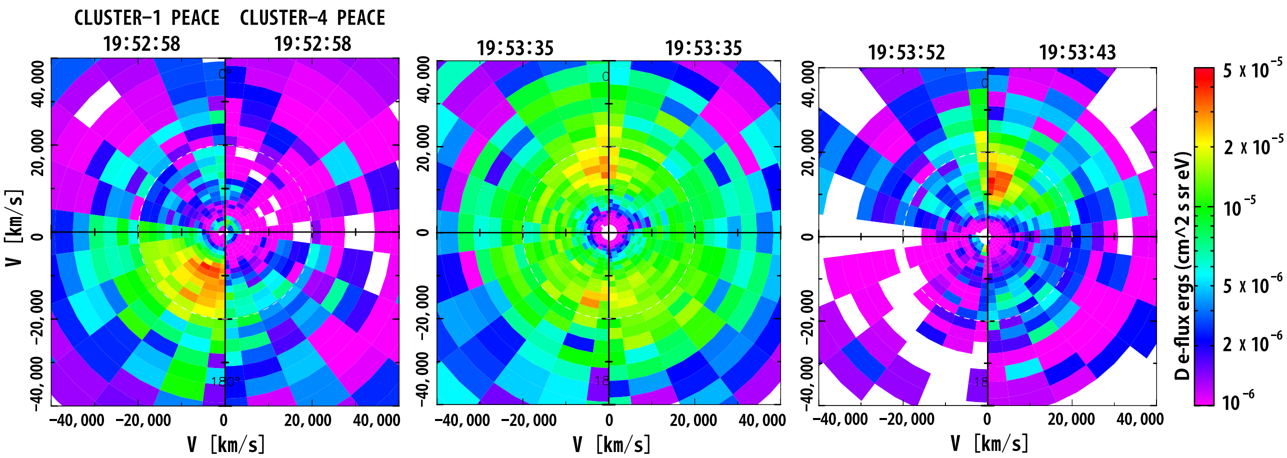

Figure 4. Electron pitch angle distributions (left) at inbound edge, (middle) in the plasma sheet boundary layer, and (right) at the outbound edge, observed by C1 (left half) and C4 (right half). The vertical axis is the parallel and horizontal axis is the perpendicular direction.

[1999]. In this technique, the curl of equivalent current can correspond to the Birkeland (field-aligned) current, assuming the uniform Hall and Pederson conductivity. After Cluster observed the PSBL crossing, the upward sense of the equivalent current curl is enhanced between the footprints of Cluster and TC1, shown in Figure 5 (left), and expands toward TC1 footprints, shown in Figure 5 (right). The spacecraft footprints are estimated using the T96 model [*Tsyganenko*, 1995]. It should be noted that the exact locations of upward/downward regions are somewhat ambiguous in ocean areas due to limited ground stations. Still, the results indicate that the region of upward sense is located between Cluster and TC1 and enhanced, associated with the PSBL crossing at the spacecraft. At the same time, a weak auroral brightening is identified in an IMAGE WIC auroral image in the southern hemisphere. Figure 6 shows that the brightening starts at 1953 and is enhanced around 1955 UT in 22–23 MLT, which is at the footprints of both the spacecraft.

3. Properties of a Local FAC

[12] A schematic figure based on the observed features of a local FAC is depicted in Figure 7. The basic concept comes from the bubble model [e.g., *Pontius and Wolf*, 1990; *Chen and Wolf*, 1993, 1999], where an earthward moving bubble is manifested by the depleted flux tube. In this model, the bubble moves earthward due to the polarization of electric fields in the bubble. Thus a surplus current goes to the ionosphere via FAC on the dawnside of a bubble and goes back to the duskside. Our observation shows several pieces of evidence for this concept: an earthward FAC by

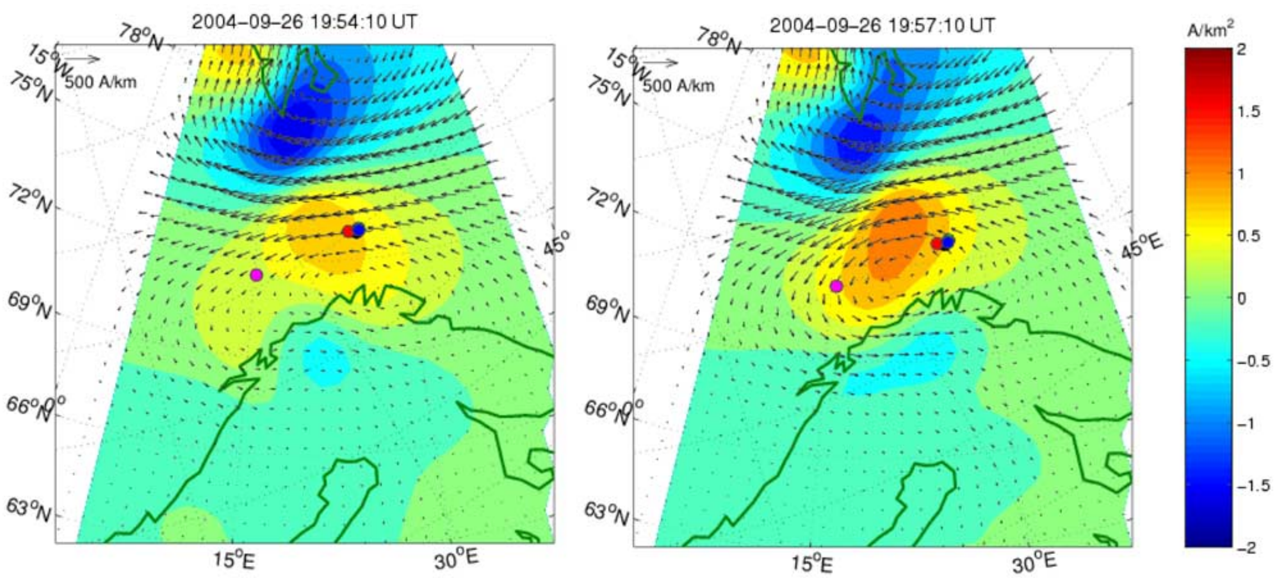

Figure 5. Curl of equivalent current calculated from the Magnetometers–Ionospheric Radars–All-Sky Cameras Large Experiment (MIRACLE) magnetometer networks. The upward and downward sense is represented by positive (red) and negative (blue) values. Equivalent current vector is also shown in arrows. Cluster (usual color) and TC1 (pink) spacecraft are mapped by T96 [*Tsyganenko*, 1995].

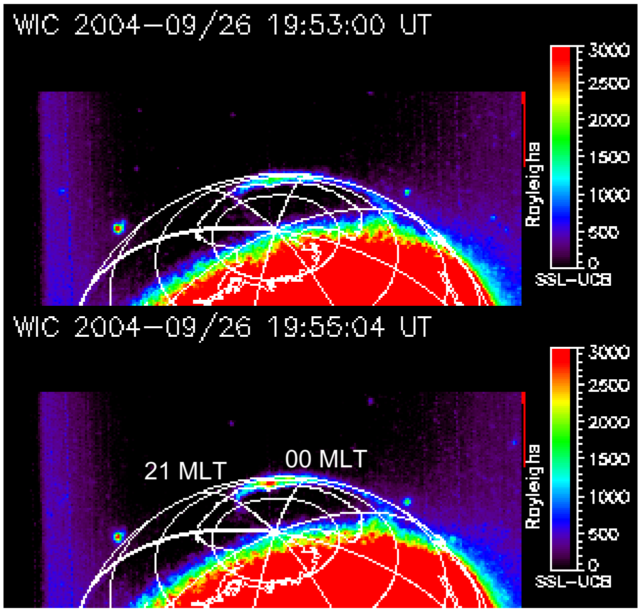

Figure 6. Auroral images in MLAT-MLT maps obtained by the IMAGE FUV/WIC in the Southern Hemisphere.

Cluster on the dawnside, a positive B_Y variation associated with a tailward FAC by TC1 on the duskside, an upward FAC on the ground between the two spacecraft slightly on the TC1 side. Although the PSBL crossing itself is not direct evidence for a BBF, an associated auroral brightening can indicate a BBF occurrence in the magnetotail at almost the same location. The time delay between Cluster and TC1 can also be explained as a propagation of fast flow. As mentioned in section 2, although there is a significant westward propagation component observed at Cluster (as illustrated in Figure 7), this propagation velocity is too slow to reach at TC1 at the observed time of PSBL entries. Yet, we cannot exclude the possibility since the elongated wavefront might not be a simple straight line, rather an inclined curve. Another plausible possibility is that the azimuthal propagation could be due to a flow-induced kink-like disturbance [*Sergeev et al.*, 2004b], which caused Cluster to temporarily observe the FAC at the PSBL. In such a case the observed time delay between Cluster and TC1 more reflects the BBF itself than the propagation of the kink wave. An important point in this study is that as a result of these PSBL disturbance, we could identify a localized FAC system earthward at the dawnside and tailward at the duskside PSBL, which are consistent with the expected BBF-associated FAC system, The presence of a local FAC in the magnetosphere and the ionosphere as well as the auroral signatures and the timing between the TC1 and Cluster supports the plasma bubble model creating such a FAC system. Yet it is impossible to check whether the flux tube is depleted or not, since the PSBL crossing is accompanied by a density enhancement due to the relative movement in the Z direction. In a recent simulation, *Birn et al.* [2004] indicate that the moving bubble is maintained by a FAC on both sides which corresponds to the twisted or sheared magnetic field. This conclusion is supported by our observation of strong sheared magnetic field, FAC, and its Alfvénic property.

[13] There are several observational features associated with a BBF in the ionosphere: an auroral streamer [*Angelopoulos et al.*, 1999; *Sergeev et al.*, 2000], an equivalent current pattern [*Amm et al.*, 2006], and convection enhancements [*Grocott et al.*, 2004]. A recent conjunction event involving Cluster and the MIRACLE network showed that when the BBF is observed in the plasma sheet, the aurora are brightening, and the associated FAC pattern is formed in the ionosphere [*Nakamura et al.*, 2005]. The equivalent current pattern in our event is consistent with the past result of the BBF event. Thus the current system in our observation is considered to be formed during the BBF passage.

[14] *Nagai et al.* [2001] found that during cases of earthward ion flow, the tailward electron beam of a lower-energy component is observed and explained as a beam associated with the Hall quadrupole signature in the reconnection. Taking this fact into account, the different features

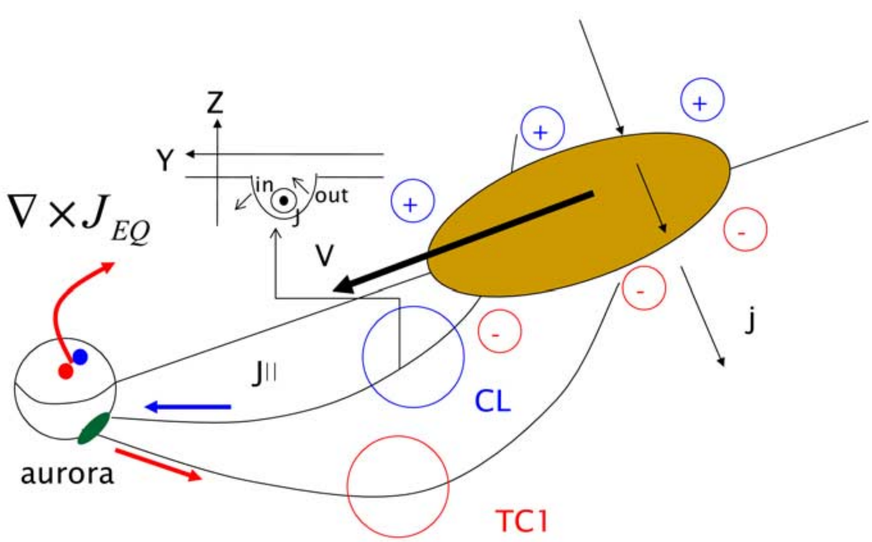

Figure 7. Illustration of a possible explanation with a summary of several observational features.

between inbound and outbound PSBL crossings can be understood by the difference of the relative spacecraft locations from the beam ejection region, i.e., the region close to the center of the current sheet. When the beam ejection region is far away from the spacecraft, the typical PSBL electron signature is identified. Conversely, when the beam-ejection region is close to the spacecraft, the electron signature associated with a reconnection is seen.

4. Summary

[15] Examining a conjunction event observed by Cluster, Double Star TC1, and MIRACLE magnetometer stations, the PSBL crossing events are interpreted as a signature of a BBF-related local FAC, associated with a small auroral brightening. Opposite polarity of B_Y on Cluster and TC1 is explained as a different direction of the FAC, whereas the Cluster curlometer confirms the expected direction of the FAC. As that FAC also connects to the ionosphere, the curl of equivalent current deduced from MIRACLE magnetometer networks shows the enhancement of upward sense current between the two spacecraft, which expands toward TC1.

[16] Focusing on the Cluster PSBL crossing, the inbound and outbound crossings show some different features: an earthward electron beam on the inbound crossing and a tailward electron beam outbound. Since the latter signature is typical for the beam ejection region, e.g., reconnection region, this may suggest the relative observational location from the beam ejection region. That is, the beam ejection region is approaching Cluster spacecraft during the PSBL crossing, which is also consistent with the formation of a local FAC associated with a BBF.

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O. Amm and L. Juusola, Finnish Meteorological Institute, FIN-00101 Helsinki, Finland.

W. Baumjohann, R. Nakamura, and M. Volwerk, Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria.

C. Carr and E. A. Lucek, Blackett Laboratory, Imperial College, London SW7 2BZ, UK.

A. N. Fazakerley and C. J. Owen, Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK.

H. U. Frey, Space Sciences Laboratory, University of California, 7 Gauss Way, Berkeley, CA 94720-7450, USA.

B. Klecker, Max-Planck-Institut für extraterrestrische Physik, D-85741 Garching, Germany.

A. Matsuoka and T. Takada, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Yoshinodai 3-1-1, Sagamihara 229-8510, Japan. (takada@stp.isas.jaxa.jp)

H. Rème, CESR, CNRS, F-31028 Toulouse CEDEX 4, France.

K. Snekvik, Department of Physics and Technology, University of Bergen, Allegt 55, N-5007 Bergen, Norway.