Annales Geophysicae, 23, 2915–2920, 2005
SRef-ID: 1432-0576/ag/2005-23-2915

Annales
Geophysicae

Cluster and Double Star observations of dipolarization

R. Nakamura[1], **W. Baumjohann**[1], **T. L. Zhang**[1], **C. M. Carr**[2], **A. Balogh**[2], **K-H. Fornacon** [3], **E. Georgescu**[4], **H. Rème**[5], **I. Dandouras**[5], **T. Takada**[1], **M. Volwerk**[1,4], **Y. Asano**[1], **A. Runov**[1], **H. Eichelberger**[1], **B. Klecker**[4], **C. Mouikis**[6], **L. M. Kistler**[6], **and O. Amm**[7]

[1]Space Research Institute, Austrian Academy of Sciences, 8042 Graz, Austria
[2]Space and Atmospheric Phys. Group, Blackett Lab., Imperial College, London SW72BZ, UK
[3]Inst. für Geophysik und Extraterrestrische Physik, Technische Universität Braunschweig, 38 106 Braunschweig, Germany
[4]Max-Planck Inst. für extraterrestrische Physik, 85 748 Garching, Germany
[5]Centre d'Etude Spatiale des Rayonnements, 31 028 Toulouse, Cedex 4, France
[6]Space Science Center, Science and Engineering Research Center, University of New Hampshire, Durham, NH 03824, USA
[7]Finnish Meteorological Institute, Space Research, 00 101 Helsinki, Finland

Received: 17 February 2005 – Revised: 15 April 2005 – Accepted: 8 April 2005 – Published: 8 November 2005

Part of Special Issue "Double Star – First Results"

Abstract. We studied two types of dipolarization events with different IMF conditions when Cluster and Double Star (TC-1) were located in the same local time sector: 7 August 2004, 18:00–24:00 UT, during a disturbed southward/northward IMF interval, and 14 August 2004, 21:00–24:00 UT, when the IMF was stably northward. Cluster observed dipolarization as well as fast flows during both intervals, but this was not the case for TC-1. For both events the satellites crossed near the conjugate location of the MIRACLE stations. By using multi-point analysis techniques, the direction/speed of the propagation is determined using Cluster and is then compared with the disturbances at TC-1 to discuss its spatial/temporal scale. The propagation direction of the B_Z disturbance at Cluster was mainly dawnward with a tailward component for 7 August and with a significant Earthward component for 14 August associated with fast flows. We suggest that the role of the midtail fast flows can be quite different in the dissipation process depending on the condition of the IMF and resultant configuration of the tail.

Keywords. Magnetospheric physics (Magnetospheric configuration and dynamics; Magnetotail; Storms and substorms)

1 Introduction

Simultaneous observations of the inner magnetosphere and the midtail are essential in substorm studies because of the initial local onset and the subsequent global expansion of the disturbance. Particularly, how these two key regions are linked in terms of fast flow and magnetic field dipolarization is yet to be determined to understand the mechanism of the substorm development.

Multi-point spacecraft separated in radial direction have been used to investigate evolution of substorm disturbances such as: relationship between energetic particle injection and plasma sheet thinning (Sauvaud et al., 1984), propagation of the current disruption (Ohtani et al., 1992, 1998; Jacquey et al., 1993) and relationship between fast flow and dipolarization (Angelopoulos et al., 1996; Shiokawa et al., 1998; Baumjohann et al., 1999). Cluster have been also used to study substorm processes such as the midtail reconnection (Runov et al., 2003) and, by combining ground-based observations with in situ measurements of other ISTP spacecrafts, the global tail dynamics and ionosphere-magnetosphere coupling (Baker et al., 2002; Sergeev et al., 2005). Yet, these large-scale substorm studies require a fortuitous constellation of the spacecraft and therefore, the number of events available are quite limited. Since the launch of the two satellites of Double Star Program (DSP, TC-1 at December 2003 and TC-2 at July 2004), Cluster and DSP fulfilled the condition of multi-point observations along the radial direction. TC-1, in an equatorial orbit with an apogee of 13 Earth radii, and TC-2, with a polar orbit and an apogee of about 7 Earth radii, were designed to study radial propagation of the disturbances in combination with Cluster observations (Liu, 2005).

In this paper we present two examples when Cluster observed dipolarizations and TC-1 was located close to its apogee at the same local time. Both events were observed in the postmidnight sector but during quite different solar wind conditions: disturbed IMF and steady northward IMF. From the timing analysis we obtain the direction and the propagation speed of the disturbance at Cluster and compare with the DSP observations in order to identify further constraints on the spatial and temporal profile of the sources based on these multi-distance multi-point observations with Cluster and DSP.

Correspondence to: R. Nakamura
(rumi@oeaw.ac.at)

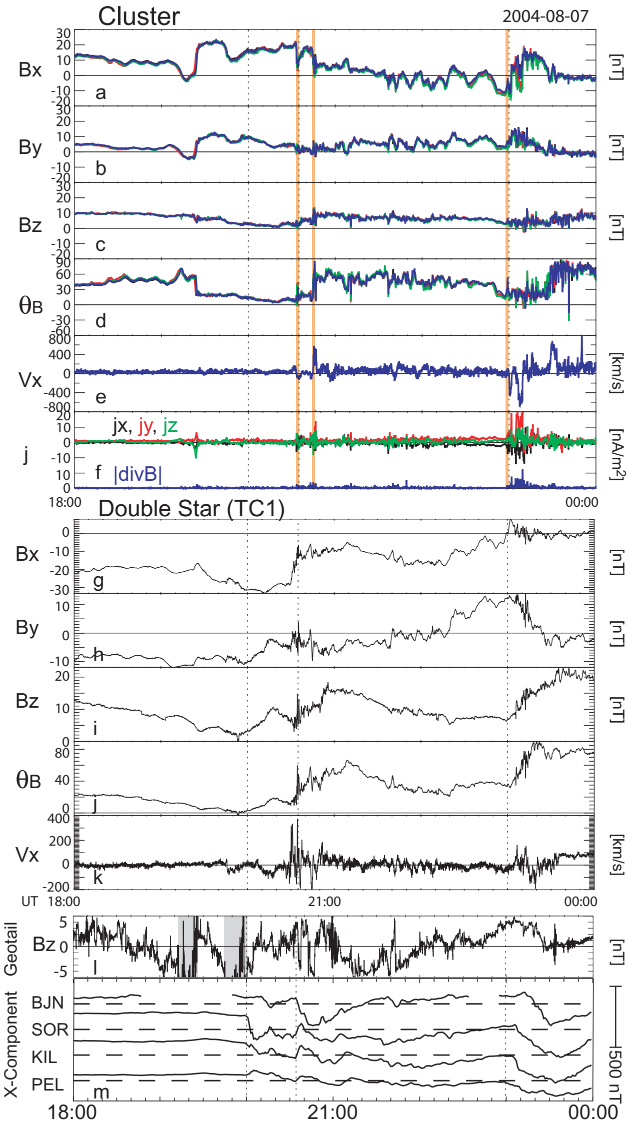

Fig. 1. **(a)** X, **(b)** Y, **(c)** Z components, and **(d)** latitude angle of the magnetic field and **(e)** X component of the proton flow from Cluster. **(f)** Current density and divergence of B estimated from the linear interpolation of the magnetic field from the four Cluster spacecraft. **(g)** X, **(h)** Y, **(i)** Z components, and **(j)** latitude angle of the magnetic field and **(k)** X component of the ion flow from Double Star TC-1. **(l)** X component of the magnetic field at Geotail in the solarwind and in the magnetosheath (shaded intervals). **(m)** X component of the ground magnetogram from selected MIRACLE stations: BJN (CGM lat. 71.45, CGM long. 108.07), SOR (67.34, 106.17), KIL (65.88, 103.79), PEL (63.55, 104.92). The vertical dotted lines show the onset time of the enhanced westward electrojet observed in the ground magnetogram, where as the orange lines indicate the onset of the B_Z enhancement observed in Cluster.

2 7 August 2004, 18:00–24:00 UT event

Magnetotail data from Cluster and TC-1, solar wind data from Geotail and ground magnetograms from selected MIRACLE stations ordered with increasing latitude are shown in Fig. 1. Throughout the paper we use the Geomagnetic Solar Magnetospheric (GSM) system for all the spacecraft data. In this study we mainly use data obtained by the fluxgate magnetometer (FGM) experiment on Cluster (Balogh et al., 2001) and on TC-1 (Carr et al., 2005) and also refer to the ion flow data from the Composition and Distribution Function Analyser (CODIF) of the Cluster Ion Spectrometry (CIS) experiment (Rème et al., 2001) onboard Cluster 4 and from the Hot Ion Analyser (HIA) instrument (Rème et al., 2005) onboard TC-1. Both Cluster and TC-1 were located in the postmidnight sector as shown in Figs. 4a–c.

Geotail was at X=15∼17, Y=1∼7, and Z=3 R_E mainly in the solar wind. Data from Geotail magnetic field measurement (Kokubun et al., 1994) in Fig. 1l show the IMF profile during this interval except for short periods between 19:15 and 20:00 UT, indicated as shaded area in the figure, when the spacecraft entered into the magnetosheath. Although B_Z was quite disturbed, there were two intervals when B_Z was mainly negative with a minimum of −5 nT: 1845∼20:10 UT and 21:05∼22:10 UT followed by a period of weak B_Z with occasional short negative excursions until around 22:45 UT when positive B_Z increased up to +5 nT and stayed northward for the following 45 min. Associated with the first negative B_Z interval, MIRACLE/IMAGE magnetograms detected an enhancement in westward electrojet activity starting at 20:00, 20:35 UT, and associated with the following negative B_Z interval, another onset at 23:00 UT as shown in Fig. 1m. Based on an 1-D upward continuation plot (not shown) of the MIRACLE meridional profile of the westward electrojet in geographic coordinate, the center of the electrojet of the 20:00 UT was identified at about 69.5° whereas the latter activity started at higher latitude >75°. On the other hand, clear poleward expansion was observed for the 23:00 UT enhancement. Corresponding to these westward electrojet activities, dispersionless injections were observed by LANL satellites at 19:55–20:00, 20:32, 22:47 and 23:13 UT (not shown). These observations suggest that there were mainly two substorm intervals with multiple intensifications. The westward electrojet onsets at the MIRACLE stations are indicated by vertical dashed lines in Fig. 1. The crossing of Cluster and TC-1 over the MIRACLE region took place at about 23:40 UT.

Associated with the first westward electrojet onset at 20:00 UT little effects were seen at both spacecraft except for a gradual enhancement in B_Z and the elevation angle in TC-1. IMF B_Z was still southward and B_X at Cluster continued to increase (θ_B keeps decreasing) indicating further stretching of the field. On the other hand, the second westward electrojet at 20:35 UT was accompanied by a clear change in the magnetic field configuration both at Cluster and TC-1. At Cluster clear jumps in B_Z and θ_B, accompanied by a decrease in B_X, took place at 20:33 and 20:44 UT, which indicate a change from a tail-like to a dipolar configuration. (B_Z and V_X from Cluster and B_Z from TC-1 during the latter dipolarization are plotted also in the left panels of Fig. 2 in a more expanded scale with orange arrows indicating the discussed dipolarization signatures.) These dipolarizations were also accompanied by an enhancement in local current

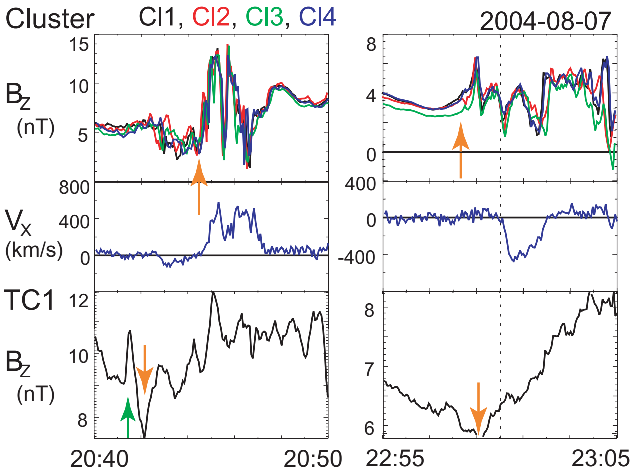

Fig. 2. Cluster B_Z and V_X and TC-1 B_Z for 20:40–20:50 UT (left) and 22:55–23:05 UT (right), on 7 August 2004. The orange arrows show the B_Z enhancements discussed in the text. The green arrow shows the estimated timing described in Sect. 4. The vertical line shows the 23:00 UT onset.

density at Cluster as shown in Fig. 1f. TC-1 was located in southern hemisphere as can be seen from the negative value of B_X and also observed enhancements in B_Z and θ_B accompanied by a decrease in the absolute value of B_X starting at 20:30 UT, and followed by a sharp increase in θ_B at 20:34 UT and 20:42 UT. Fast Earthward ion bulk flows were detected at TC-1 and Cluster starting at 20:34 UT and 20:44 UT, respectively. Associated with the 23:00 UT onset, Cluster in the southern hemisphere observed rapid crossings of the current sheet with enhanced current density. θ_B and B_Z first showed a rapid positive jump at 22:58 UT, but then a decrease associated with tailward flow which suggests a tailward moving flux-rope like feature tailward of an X-line as can be seen in the right panels of Fig. 2. Change from tailward fast flow to Earthward flow with relevant B_Z changes was observed at Cluster, possibly related to the tailward retreat of an X-line. TC-1, on the other hand, observed clear dipolarization starting at 22:59 UT with rather weak flow disturbance. Cluster energetic particle signatures for this interval are discussed in Deng et al. (2005).

3 14 August 2004, 21:00–24:00 UT event

Figure 3 shows data from Cluster and Double Star TC-1 together with the Geotail and MIRACLE magnetograms between 21:00 and 24:00 UT on 14 August 2004, in the same format as Fig. 1. Geotail was located at X=8∼9, Y=29, and Z=-1∼$-2\,R_E$, again mainly in the solar wind except for the magnetosheath encounter after 23:50 UT (Fig. 3l). It can be seen that the IMF B_Z was all the time northward with a typical value of ∼3 nT. Although weak, two westward electrojet disturbances can be identified in the MIRACLE magnetograms at 21:57 UT and around 23:12 UT, both centered at 71–72°. The 21:57 UT activation was due to a lower latitude shift of a very high-latitude (77–78°) westward electrojet, which then returned to high latitudes back again (not shown). The 23:12 UT disturbance was followed by a new enhancement at high-latitude starting at 23:20 UT (see BJN profile in Fig. 3m) with signatures of equatorward motion of the electrojet (not shown). No energetic particle injection was detected by LANL satellites (not shown). These signatures suggest a feature quite different from a usual “substorm”, with disturbances taken place mainly at high latitudes with equatorward propagation but not involving the inner magnetosphere. The crossing of TC-1 and Cluster over the MIRACLE region was at about 23:00 UT.

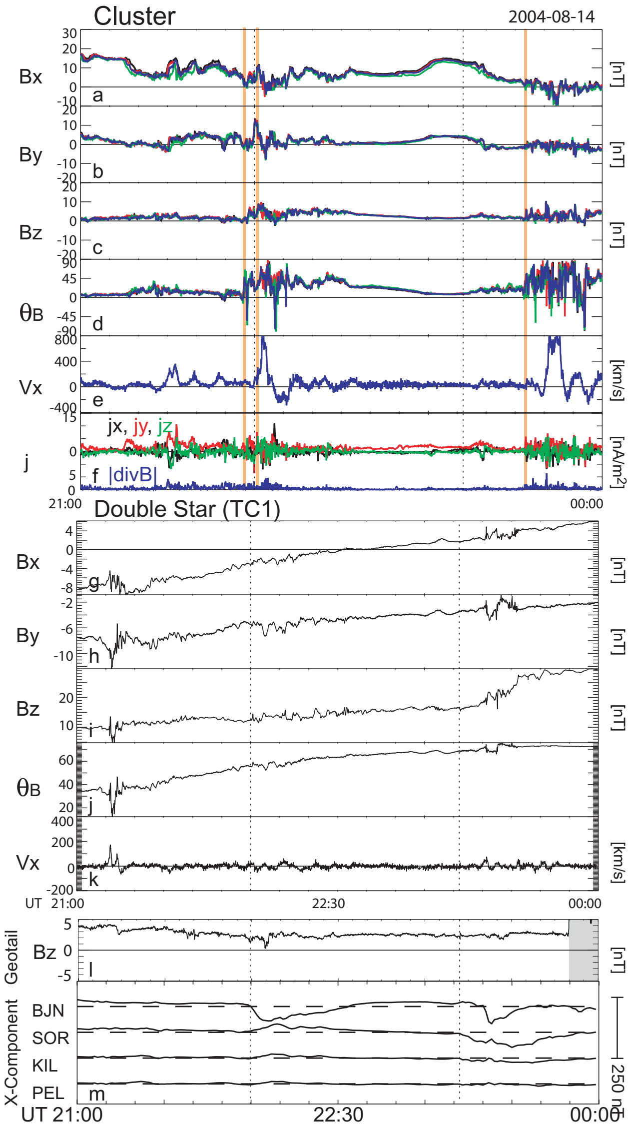

Fig. 3. Same as Fig. 1 except for 14 August 2004.

Cluster detected sharp enhancement in B_Z and θ_B followed by fast Earthward ion flow at 21:56 UT and 23:34 UT. The latter flow is almost 15 min delayed from the activation of the ground, although weak magnetic fluctuation started already after 23:12 UT. On the other hand, TC-1 showed no

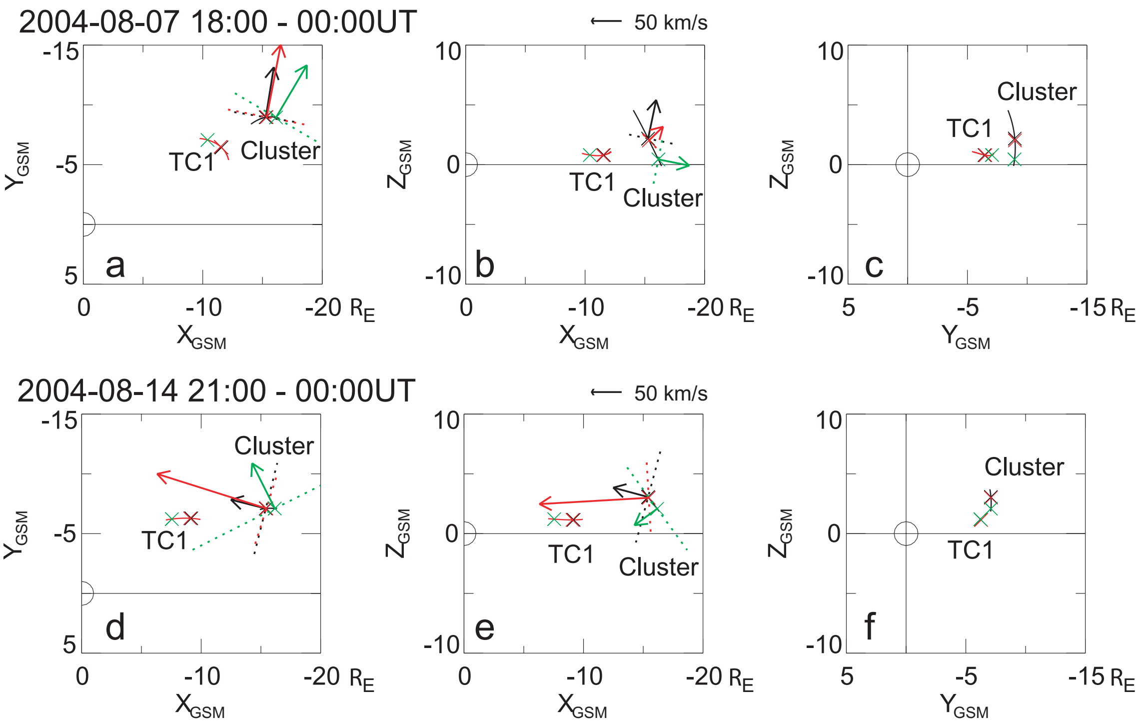

Fig. 4. Cluster and Double Star TC-1 orbit between 18:00 and 24:00 UT on 7 August 2004 (upper three panels) and between 21:00 and 24:00 UT on 14 August 2004 (lower three panels) in the X-Y plane **(a, d)**, in the X-Z **(b, e)**, and in the Y-Z plane **(c, f)** plotted in GSM. The color crosses show the spacecraft location and the arrows show the motion of the dipolarization front for each event expressed with different colors: 7 August, 20:33 UT (black), 20:44 UT (red), and 20:58 UT (green); 14 August, 21:55 UT (black), 22:02 UT (red), 23:33 UT (green). The dashed lines show the possible spatial scale if it is assumed that the front also will encounter (or had encountered) TC-1.

signature of clear dipolarization, but some magnetic disturbances after 22:00 UT onset and after 23:20 UT with no ion flow signature.

4 Propagation of magnetic field disturbance

To characterize the propagation of the dipolarization more quantitatively, we compared the local propagation properties of the B_Z disturbance among the four Cluster spacecraft with that of the larger scale propagation between Cluster and Double Star. We first determine the motion of the dipolarization signature from the timing analysis of Cluster, assuming the dipolarization front to be a planar structure. For the analysis we use time difference of B_Z or θ_B among the spacecraft for the events when clear enhancements were observed in B_Z and θ_B and when all the Cluster spacecraft had similar profile so that a timing analysis should be valid. Timing, propagation direction and speed of dipolarization at Cluster are then compared with observed signatures at TC-1. As described in the previous section, there were events where both Cluster and TC-1 observed similar features (7 August event) and when only Cluster observed strong signatures (14 August event). The former cases are useful to confirm the propagation speed and, if consistent timing is obtained, we can also determine the minimum spatial scale of the disturbance. The 14 August event, on the other hand, can be used to obtain the maximum scale of the disturbance, not to be observed at TC-1.

For the 7 August event we calculated the propagation speed and direction for the B_Z (or θ_B) enhancement around 20:33, 20:44, and 22:58 UT. The propagation vector, $\boldsymbol{V}$, for these three events is plotted in Figs. 4a and b with black (20:33 UT event), red (20:44 UT event), and green (22:58 UT event) arrows. Location of TC-1 and Cluster at these three moments are shown with crosses in the same corresponding colors. The propagation of the disturbances were mainly dawnward with a tailward component. This suggests that the initial source of the disturbance is located duskward and Earthward of Cluster toward the TC-1 location. This procedure further allows to determine the arrival time of the disturbance at TC-1, which can be expressed as $t_{\mathrm{TC-1}}=t_{\mathrm{CL}}-((\boldsymbol{R}_{\mathbf{CL}}-\boldsymbol{R}_{\mathbf{TC-1}})\cdot \boldsymbol{V})/(\boldsymbol{V}\cdot\boldsymbol{V})$ assuming the spacecraft motion is negligible. Also we can determine the projected distance between Cluster and TC-1 along this plane such as $|\boldsymbol{D}|=|\boldsymbol{R}_{\mathbf{CL}}-\boldsymbol{R}_{\mathbf{TC-1}}-(t_{\mathrm{CL}}-t_{\mathrm{TC-1}})\boldsymbol{V}|$. The dashed lines perpendicular to these arrows show the projected components of displacement vector $\boldsymbol{D}$. Using this simple assumption, i.e. that the dipolarization is a planar front moving with a constant speed, we estimated that at TC-1 the disturbance should take place at 20:30, 20:41, and 22:51 UT. For the 20:41 UT event, this estimated timing is indicated with a green arrow in the TC-1 panel (bottom left) in Fig. 2. TC-1 in fact observed some enhancements in θ_B and B_Z around 20:30 UT and 20:42 UT, but no corresponding signature was observed for the latter disturbance. For the first two disturbances, both spacecraft could likely have detected the same disturbances propagated from TC-1 to Cluster and they were possibly related to the dipolarization front associated with Earthward flows. The propagation speed, 60–190 km/s, was within the value of the previously obtained tailward propagation speed of 35–300 km/s (Ohtani et al., 1992; Jacquey et al., 1993; Baumjohann et al., 1999). Yet, the major direction was dawnward such as the case of dawnward expansion of the dipolarization observed in the postmidnight in the geosynchronous region (Nagai, 1982). The minimum required scale-size of the disturbance was then 3.3 R_E and 3.4 R_E for the first and second disturbances, respectively, coming from the duskward-Earthward side from TC-1. On the other hand, the last disturbance cannot be understood in terms of propagation of the same disturbance. In fact, as described before, the B_Z enhancement at Cluster was rather related to a tailward moving flux rope-type signature, whereas the TC-1 observed dipolarization almost simultaneously with Cluster (see Fig. 2 right panels). This indicates that the source region is most likely located between Cluster and TC-1 and the propagated disturbance reached both Cluster and TC-1 nearly simultaneously.

The direction of the propagation of the dipolarization front was Earthward for the 14 August event as shown in Figs. 4d and e with black (21:55 UT event), red (22:02 UT event), and green (23:33 UT event) arrows. Similar Earthward/dawnward motion has been reported by Cluster at the postmidnight region associated with BBF (Nakamura et al., 2002). Since we have no signature detected at TC-1, estimation of the expected arrival time and scale-size of the disturbance has a different meaning for this event. If we estimate in the same way the arrival time of the B_Z enhancement at TC-1, the 21:55 UT, 22:02 UT and 23:33 UT disturbances at Cluster are expected to be observed 9 min, 3 min and 4 min later at TC-1, when the scale size of the disturbance is larger than 4, 3, and 8 R_E, respectively. The lack of such observations at TC-1 suggests that the disturbance was localized (or occurred at shorter time scale than these values). Either the BBF associated dipolarization was a transient phenomena and quenched between Cluster and TC-1 or the localized BBF/dipolarization front could not be observed at TC-1 resulting in only small magnetic field fluctuation, which could be similar types of ULF oscillations observed earlier of this event (Volwerk et al., 2005), but associated with fast flows. The lack of any injection signature at LANL as well as the location of the westward electrojet suggests that in fact the energy transported by the BBF is very likely dissipated mostly before reaching the TC-1 region. On the other hand, the observation is consistent with a statistical study of the BBF scale size, 2–3 R_E by Cluster (Nakamura et al., 2004).

5 Summary and discussions

Dipolarization and fast flow disturbance were detected by Cluster during quite different conditions on 7 August and 14 August 2004. During the major substorm intensification on 7 August, propagation of the dipolarization front, most likely from the same source, could be identified at TC-1. On the other hand, during northward IMF interval of 14 August, there was no clear dipolarization or flow signatures observed at TC-1 which could be related to the fast flow associated dipolarization front observed at Cluster, even though the distance between Cluster and TC-1 perpendicular to the propagation direction was similar for the 14 August event. The flow-associated disturbances were more transient or localized during the 14 August event. These differences suggest that the role of the bursty bulk flow can be quite different for different IMF condition and resultant tail configurations.

Studies on global propagation of the disturbance including detailed plasma and ionospheric signatures are planned in the future. Yet, this preliminary analysis shows the complicated nature of the propagation of the disturbance in the tail and a new possibility of combining local and global multi-point analysis to further quantify the characteristics of the source regions.

Acknowledgements. We acknowledge Z. Liu and P. Escoubet for the successful Double Star program. We thank G. Laky for helping in the Cluster/Double Star data analysis, and T. Nagai for providing Geotail data. We acknowledge CDAWeb, WDC-C2, CSDS, GCDC, ACDC, CSSR, and EDDS for making available data used in this study. The work by M. Volwerk and K.-H. Fornacon was financially supported by the German Bundesministerium für Bildung und Forschung and the Zentrum für Luft- und Raumfahrt under contract 50 OC 0104. A part of the work at IWF is supported by INTAS 03-51-3738 grant.

Topical Editor T. Pulkkinen thanks V. Angelopoulos and another referee for their help in evaluating this paper.

References

Angelopoulos, V., Coroniti, F. V., Kennel, C. F., et al.: Multipoint analysis of a bursty bulk flow event on 11 April 1985, J. Geophys. Res., 101, 4967–4989, 1996.

Baker, D. N., Peterson, W. K., Eriksson, S., et al.: Timing of magnetic reconnection initiation during a global magnetospheric substorm, Geophys. Res. Lett., 29(24), 2190, doi:10.1029/2002GL015539, 2002.

Balogh, A., C. M. Carr, M. H. Acuña, et al.: The Cluster magnetic field investigation: overview of in-flight performance and initial results, Ann. Geophys., 19, 1207–1217, 2001, **SRef-ID: 1432-0576/ag/2001-19-1207**.

Baumjohann, W., Hesse, M., Kokubun, S., Mukai, T., Nagai, T., and Petrukovich, A. A.: Substorm dipolarization and recovery, J. Geophys. Res., 104, 24 995–25 000, 1999.

Carr, C. M., Dunlop, M. W., Beek, T. J., et al.: The Double Star magnetic field investigation: instrument design, performance and highlights of the first years observations, Ann. Geophys., 23, 2713–2732, 2005.

Deng, X. H., Tang, R. X., Nakamura, R., et al.: Observation of reconnection pulses by Cluster and Double Star, Ann. Geophys., 23, 2921–2927, 2005.

Jacquey, C., Sauvaud, J. A., Dandouras, I., and Korth, A.: Tailward propating cross-tail current disruption and diynamics of near-Earth tail: A multi-point measurement analysis, Geophys. Res. Lett., 20, 983–986, 1993.

Kokubun, S., Yamamoto, T., Acuna, M. H., Hayashi, K., Shiokawa, K., and Kawano, H.: The Geotail magnetic field experiment, J. Geomagn. Geoelectr., 46, 7, 1994.

Liu, Z. X., Escoubet, C. P., Pu, Z., Laakso, H., Shi, J. K., Shen, C., and Hapgood, M.: The Double Star mission, Ann. Geophys., 23, 2707–2712, 2005.

Nagai, T.: Observed magnetic substorm signatures at synchronous altitude, J. Geophys. Res., 87, 4405–4417, 1982.

Nakamura, R., Baumjohann, W., Klecker, B., et al.: Motion of the dipolarization front during a flow burst event observed by Cluster, Geophys. Res. Lett., 29, 1942, doi:10.1029/2002GL015763, 2002.

Nakamura, R., Baumjohann, W., Mouikis, C., et al.: Spatial scale of high-speed flows in the plasma sheet observed by Cluster, Geophys. Res. Lett., 31, L09804, doi:10.1029/2004GL019558, 2004.

Ohtani, S., Kokubun, S., and Russel, C. T.: Radial expansion of the tail current disruption during substorms: a new approach to the substorm onset region, J. Geophys. Res., 97, 3129–3136, 1992.

Ohtani, S.: Earthward expansion of tail current disruption: Dual-satellite study, J. Geophys. Res., 103, 6815–6825, 1998.

Rème, H., Aoustin, C., Bosqued, J. M., et al.: First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment, Ann. Geophys., 19, 1303–1354, 2001,
SRef-ID: 1432-0576/ag/2001-19-1303.

Rème, H., Dandouras, I., Aoustin, C., et al.: The HIA instrument on board the Tan Ce 1 Double Star near-equatorial spacecraft and its first results, Ann. Geophys., 23, 2757–2774, 2005.

Runov, A., Nakamura, R., Baumjohann, W., et al.: Current sheet structure near magnetic X-line observed by Cluster, Geophys. Res. Lett., 30(11), 1579–1582, doi:10.1029/2002GL016730, 2003.

Sauvaud, J. A., Saint-Marc, A., Dandouras, J., et al.: A multisatellite study of the plasma sheet dynamics at substorm onset, Geophys. Res. Lett., 11(5), 500–503, 1984.

Sergeev, V. A., Kubyshkina, M. V., Baumjohann, W., et al.: Transition from substorm growth to substorm expansion phase as observed with a radial configuration of ISTP and Cluster spacecraft, Ann. Geophys., 23, 2183–2198, 2005,
SRef-ID: 1432-0576/ag/2005-23-2183.

Shiokawa, K., Baumjohann, W., Haerendel, G., et al.: High-speed ion flow, substorm current wedge, and multiple Pi 2 pulsations, J. Geophys. Res., 103, 4491–4507, 1998.

Volwerk, M., Zhang, T. L., Nakamura, R., et al.: Plasma flow channels with ULF waves observed by Cluster and Double Star, Ann. Geophys., 23, 2929–2935, 2005.