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Motion of the dipolarization front during a flow burst event observed by Cluster

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[1] In this paper we study a flow burst event which took place during enhanced geomagnetic activity on July 22, 2001, when Cluster was located in the postmidnight magnetotail. The flow burst was associated with a clear dipolarization ahead of the high-speed part of the predominantly Earthward directed flow. Based on the analysis of the four spacecraft data, we found that a ∼2000 km thick dipolarization front moves Earthward and dawnward with a speed of ∼77 km/s. The plasma before this front is deflected, consistent with the plasma ahead of a localized plasma bubble centered at midnight side being pushed aside by the moving obstacle. The main body of the high-speed flow is directed mainly parallel to the dipolarization front. These observations indicate that the evolution of the dipolarization front across the tail is directly coupled with the fast flow. *INDEX TERMS:* 2760 Magnetospheric Physics: Plasma convection; 2744 Magnetospheric Physics: Magnetotail; 2764 Magnetospheric Physics: Plasma sheet; 2731 Magnetospheric Physics: Magnetosphere—outer. **Citation:** Nakamura, R., et al., Motion of the dipolarization front during a flow burst event observed by Cluster, *Geophys. Res. Lett.*, *29*(20), 1942, doi:10.1029/2002GL015763, 2002.

1. Introduction

[2] Transient high-speed plasma flows, which are called bursty bulk flows (BBF) or flow bursts, play a major role in the magnetotail mass, energy and magnetic flux transport in the magnetotail [*Baumjohann et al.*, 1989, 1990; *Angelopoulos et al.*, 1994; *Schödel et al.*, 2001]. Many studies using quite different methods have shown that a BBF is limited in dawn-dusk extent with a spatial scale of 1–5 R_E [e.g., *Sergeev et al.*, 1996; *Angelopoulos et al.*, 1997; *Nakamura et al.*, 2001b]. Possible mechanisms for these flows are due to patchy impulsive reconnection process and/or an interchange instability of a plasma depleted flux bubble [*Chen and Wolf*, 1993; *Sergeev et al.*, 1996].

[3] Relationships between midtail and near-tail BBFs, i.e., how these bursty flows at different location in the tail evolve and interact with the inner magnetosphere, are not well understood. Statistical studies showed that although the flow speed decrease as moving inward, the occurrence rate of the rapid flux transport is constant between 40 and 15 R_E and significantly drops only earthward of 15 R_E when braking of the flow takes place in a strong field/high pressure region [*Schödel et al.*, 2001]. Yet the fact that auroral precipitation always takes place associated with the flow burst [*Nakamura et al.*, 2001a] suggests that each flow burst loses energy on its way to the near-Earth region by interacting with ambient plasma/field and creating field aligned currents. It is therefore essential to study the evolution of the flow burst by identifying the temporal and spatial relationship between the flows and the magnetic field disturbances.

[4] Since July 2001 Cluster started to observe the magnetotail, covering regions Earthward of 19 R_E where fast flows are frequently detected. A result from the four spacecraft analysis during a flow burst event with dipolarization is shown in this paper. By analyzing the plasma and magnetic field data from the four Cluster spacecraft we succeeded to measure the expansion speed of the dipolarization region associated with the flow disturbances.

2. Event Overview

[5] Figure 1 shows spin-resolution (∼4 s) data from the fluxgate magnetometer (FGM) experiment [*Balogh et al.*, 2001] and from the Cluster ion spectrometry (CIS) experiment [*Rème et al.*, 2001] during a dipolarization event accompanied by a flow burst. All the parameters are shown in Geocentric Solar Magnetospheric (GSM) coordinates. During this interval Cluster was located at postmidnight at $X_{GSM} = -14.5\ R_E$, $Y_{GSM} = -11.6\ R_E$, $Z_{GSM} = 4.2\ R_E$. This dipolarization event occurred during a prolonged interval of fluctuating negative IMF B_Z based on WIND data (not shown) when continuous geomagnetic activations of 200–250 nT in *AL* (provisional *AL*) related to substorm intensification as well as enhanced convection took place, starting with a substorm onset around 0922 UT when a sharp negative bay was observed at Yellowknife around 23 MLT (not shown). Cluster stayed in the plasma sheet after 11 UT. At 1134 UT and 1146 UT, College at postmidnight (around 2 MLT) observed an intensification resulting in a negative bay of about 200 nT (not shown). Cluster observed two dipolarization events accompanied by short-time scale (several min) flow bursts exceeding 300 km/s around 1135 and 1148 UT. The event shown in Figure 1 corresponds to the first intensification with larger flow and stronger dipolarization, which will be studied in detail in this paper.

[6] The magnetic field shows a clear signature of dipolarization starting with SC 2 (dashed trace). The proton flow

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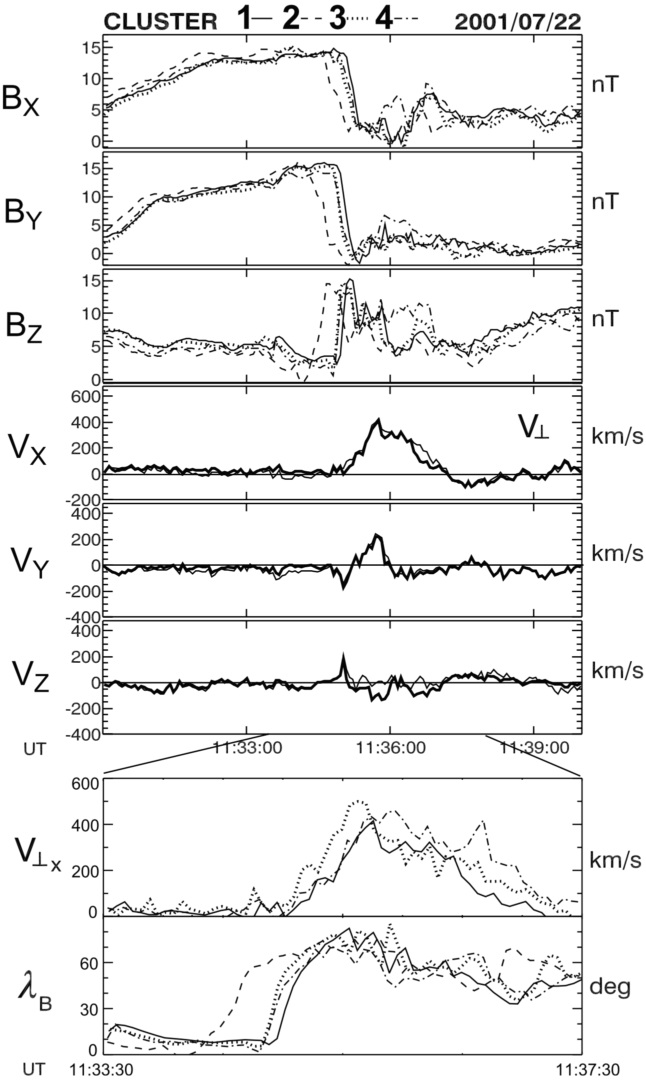

Figure 1. (a) Magnetic field and ion flow obtained by Cluster during a high speed flow interval on July 22, 2001. The solid, dashed, dotted, dash-dotted lines correspond to SC 1, 2, 3, and 4 respectively. The thick line of the flow data indicates the velocity component perpendicular to the magnetic field, while the thin line is the total flow. (b) *X* component of the flow and latitude angle of the magnetic field in an expanded time scale.

data, V_X, V_Y, and V_Z, which are obtained from the Composition and Distribution Function Analyser (CODIF) onboard SC 1, show an enhancement associated with the dipolarization, predominantly in the *X* direction. The enhanced flow, which has a maximum speed of 540 km/s, is predominantly directed perpendicular to the ambient magnetic field, as can be seen from the good coincidence between the thin and solid lines in the V_X, V_Y and V_Z plots. To show the differences among the different spacecraft, the bottom two plots show the latitude angle, $\lambda_B = \tan^{-1} B_Z/(B_X^2 + B_Y^2)^{1/2}$ and the *X* component of the perpendicular flow on a more expanded timescale. The flow data shown in this figure are the CODIF proton moments from SC 1 and 3, and 4, from which ion data were available. Magnetic field as well as flow data show similar profiles among the different satellites, except for the time delay. By examining the 1s resolution magnetic field data we obtained that the dipolarization event of SC 2 leads that of SC 1, 3, and 4 by 22 s, 18 s, and 20 s, respectively. Note that a 20 s time delay for the spatial scale of the Cluster tetrahedron, about 2000 km, suggests much slower propagation speed than the fast flows, which will be examined in more detail in the following section.

3. Relative Location and Timing

[7] Using these temporal differences among the satellites at different location we examined the possible propagation direction of the flow and magnetic field disturbances. The relative location of the four spacecraft in the GSM $X - Y$ and $X - Z$ plane is shown in Figures 2a and 2b. The thick arrows show the direction of the average flow direction at the maximum of the high-speed flow, which is between 11:35:28–11:35:48 UT. All the flow vectors from the three satellites (SC 1, 3, and 4) are directed Earthward, but slightly tilted duskward, i.e., toward midnight.

[8] In order to analyze the temporal differences among the four spacecraft observations, we used a new coordinate system. Here we referred to the magnetic field disturbances using the method introduced by *Sergeev et al.* [1996] for the analysis of the bubble based on plasma bubble model [*Chen and Wolf*, 1993]. *Sergeev et al.* [1996] showed that Earthward moving plasma structures, such as the bubbles, are separated from the plasma ahead of them by a discontinuity,

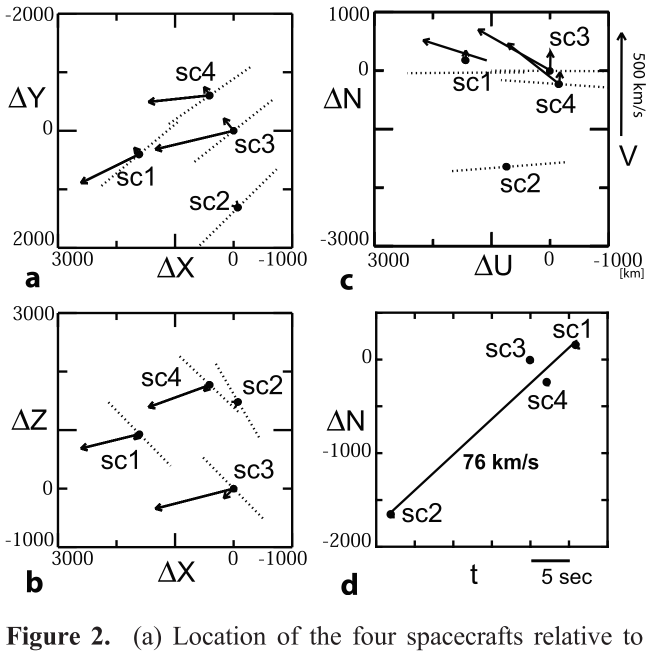

Figure 2. (a) Location of the four spacecrafts relative to the reference spacecraft (SC 3) in GSM $X - Y$ plane. The dotted lines show the projection of the dipolarization front. The thick arrows are the plasma flows at the interval of maximum flow speed while the thin arrows correspond to plasma flow normal to the dipolarization front during the interval of the dipolarization, as identified in the text. (b) Same as Figure 2a, except for GSM $X - Z$ plane. (c) Same as Figure 2a, but plotted in $N - U$ plane of a dipolarization-flow coordinate system (see text for detail) (d) Temporal and spatial relationship of the four satellite observation of the dipolarization plotted in the $t - N$ plane. The slanted line shows a velocity of 76 km/s.

which corresponds to the front layer identified from the change in B_Z. The orientation of the discontinuity can be determined by the minimum variance of the magnetic field of the dipolarization. Similar to this bubble picture, the flow bursts shown in this study also accompany such dipolarization front. Plasma pressure during the flow interval does not differ from that afterwards, i.e., almost similar for SC 1 and 3 (not shown) and a subtle decrease of less than 20 percent for SC 4 (not shown). After the model of *Chen and Wolf*, [1999], the plasma bubble is possibly at an evolved stage, in which a bubble does not necessarily correspond to a plasma depleted region. Here we used spin-averaged magnetometer data and performed a minimum variance analysis for a 80 s time interval, which includes the dipolarization period plus about the same time interval before and after. The start time used for the analysis of the SC 1, 2, 3 and 4 are 11:34:24, 11:34:02, 11:34:20, and 11:34:22 UT, respectively. The obtained dipolarization plane, i.e. normal to the minimum variance direction, is shown as dotted lines. It can be seen that the direction of this plane is nearly identical for all the four spacecraft. The differences among the minimum variance direction are within 12° and 7° on average. This suggests that the observed feature can be understood as a nearly planar structure. In fact, if we use the timing analysis for the four spacecraft, assuming the time delay to be due to a planar structure passing with constant velocity, we obtain a similar direction: the average direction of the normal vector determined from the minimum variance analysis, N, is (0.55, −0.66, −0.48), while the result from the timing analysis is (0.63, −0.70, −0.29), i.e., different by about 12°. The thin arrows show the average flow velocity normal to the dipolarization front during the time interval of the dipolarization, which is 77 km/s on average. This is very close to that obtained from the timing analysis, i.e., 78 km/s, supporting again a planar structure of the boundary.

[9] Using the result from the minimum variance analysis, we plotted in Figure 2c the relative location of the four spacecraft in a dipolarization-flow ($N - U$) coordinate system where N is the average minimum variance direction and is the normal direction to the dipolarization front, and U is the flow direction projected on the plane perpendicular to N, i.e., $(N \times \boldsymbol{V}) \times N$, and $\boldsymbol{V}$ is the average direction of the high speed flow vectors shown in the figure. The spatial separation of the four satellites along the N direction shown in Figure 2c is consistent with the time difference in the temporal profiles of the dipolarization shown in Figure 1. The temporal/spatial relationship is further emphasized in Figure 2d by plotting the satellite position along the N direction versus the relative time differences. The distribution of the spacecraft in Figure 2d agrees with a dipolarization front expanding with a constant speed of about 76 km/s along the N direction. Note that this speed is again similar to the one determined from the timing analysis as well as the one expected from the average plasma velocity. The high-speed flow burst therefore is preceded by a plasma moving with the dipolarization front away from the main stream direction.

4. Evolution of the Flow Burst

[10] Figure 3 shows the flows and magnetic field data from SC 1, 3, and 4 plotted in the $N - U$ coordinate system. The high-speed flow, which is strongest in the U component occurs in association with the dipolarization. During the dipolarization, the U component of the magnetic field decreases to almost zero, with the magnetic field mainly in the $N \times U$ direction. If we look into the flow profile in more detail, the flow direction changes in three steps, as indicated by the vertical lines. That is, the flow direction is changing from a peak in (1) the $N \times U$ component, over (2) a peak in the U component, to (3) a flow predominantly in the N direction. The vertical lines in the figure are markers taken from the profile of SC 1 (black) as a reference. Similar changes can be identified also for SC 3 and 4 with corresponding time differences as discussed in the previous section. The change of the flow orientation in the equatorial plane is illustrated in Figure 4 by simply converting temporal change into spatial change. The vectors give averages of flow data from all three satellites around the peak of each phase: (1) 11:34:49–11:35:05, (2) 11:35:28–11:35:49, (3)11:36:01–11:37:02. The dotted line gives the average dipolarization front.

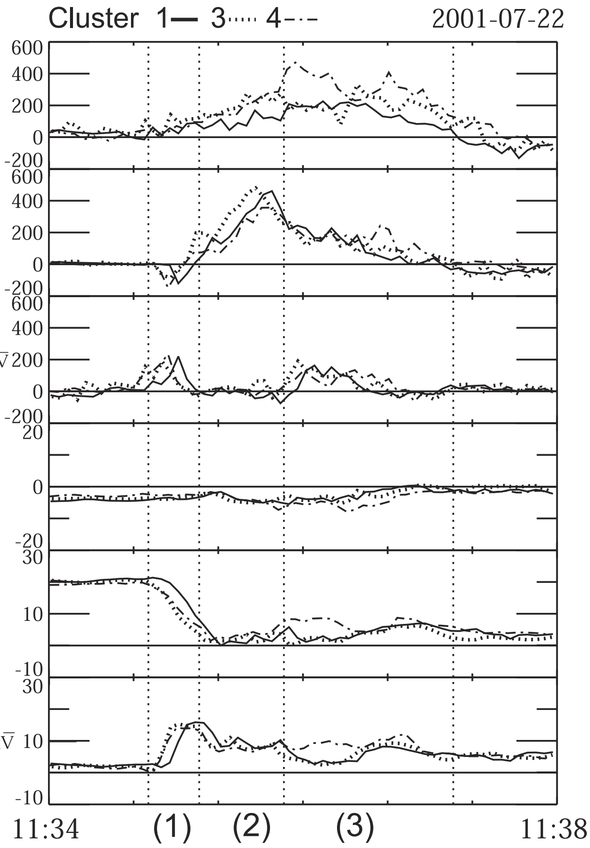

Figure 3. Magnetic field and ion flow from SC 1, 3, and 4 in the dipolarization-flow coordinate system. The vertical lines indicate the time intervals (1), (2) and (3), when the flow direction changes from mainly in the (1) $N \times U$ direction, over (2) predominantly directed along U, to (3) N-aligned for SC 1.

[11] From Figures 3 and 4 one can see how the flow burst evolves relative to the dipolarization front. (1) At the initial stage of the dipolarization, the ambient plasma moves outward, i.e., dawnward and northward (the latter not shown), away from the dipolarization region, in a frame moving with the dipolarization front. The dipolarization front is oriented nearly radially. (2) The main body of the high-speed Earthward jetting plasma is directed slightly

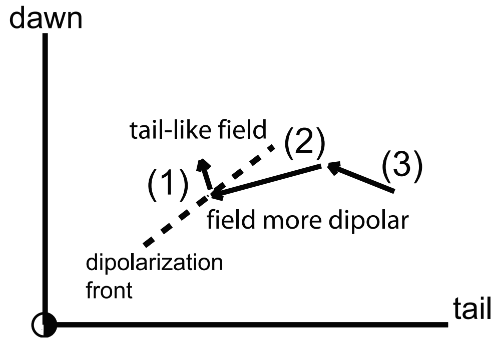

Figure 4. Average profile of the flow at phases (1), (2), and (3) and the dipolarization front in the equatorial plane.

duskward, close to the direction of the dipolarization front. Yet the flow is more tail-aligned than the dipolarization front so that there is a component of the flow normal to the dipolarization front. (3) During the last phase, the flow well behind the dipolarization front is directed earthward but tilted slightly dawnward, as if spreading out unimpeded from a local source located tailward and closer to the midnight meridian.

5. Discussion and Conclusion

[12] Using four spacecraft measurements we obtained that the orientation of the dipolarization front leading the flow burst has a nearly planar configuration. This suggests that the spatial scale of the flow structure should be much larger than the maximum separation (2000 km) of the spacecraft along this front layer. Such a nearly planar structure observed by Cluster is expected from the typical spatial scale predicted for the bursty bulk flows or bubbles from previous studies, 1–5 R_E. On the other hand, the thickness of the dipolarization front is ~2000 km based on the observation ~26 s duration of the dipolarization front with ~77 km/s propagation speed. The Cluster configuration therefore allows to unambiguously determine the relationship between the motion of the dipolarization front and the plasma motion.

[13] Systematic changes were observed in the flow structure, which can be interpreted as the evolution of a flow burst interacting with the ambient plasma/field and approaching the near-Earth region. The first plasma/field signatures observed were the Earthward and dawnward expansion of the dipolarization region, and the ambient plasma pushed aside from the dipolarization front creating a flow shear as shown in (1) in Figure 4. This flow pattern is similar to that at the dawnward side of the bubble discussed by *Sergeev et al.* [1996]. The dipolarization front is tilted toward the radial direction from the Earth consistent with the direction of the ambient field before the flow event.

[14] The high-speed earthward jetting plasma behind this front phase, (2) in Figure 4, is also slightly tilted toward dusk similar to the dipolarization front. Yet the flow is more tail-aligned than the dipolarization front so that there is a component of the flow normal to the dipolarization front. The Earthward flow for the later period (3), on the other hand, is tilted slightly dawnward, as if spreading out from a local source located tailward and closer to the midnight meridian. This change in the direction of the high-speed flow is possibly related to the fact that the fast flow, initially jetting from a localized source closer to the midnight is eventually deflected by the ambient field to align more along the near-Earth dipole field orientation. The flow pattern obtained by the reconnection process in the midtail by *Birn et al.* [1999] showed also this conversion of the flow toward midnight (duskward component at postmidnight and dawnward component at premidnight) in the midtail region such as we observed in the flow (2) in Figure 4. On the other hand, their flow pattern at the dipolarization region, where the flow is braked, is similar to the one obtained in (1), namely a dawnward component in the postmidnight sector. The changes in the flow direction observed in this study seem to therefore reflect both the condition of the ambient global magnetic field configuration and the internal structure of the flow burst at different region relative to the dipolarization front.

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