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Cluster observation of plasma flow reversal in the magnetotail during a substorm

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Abstract. We investigate in detail a reversal of plasma flow from tailward to earthward detected by Cluster at the downstream distance of $\sim$19 R_E in the midnight sector of the magnetotail on 22 August 2001. This flow reversal was accompanied by a sign reversal of the B_z component and occurred during the late substorm expansion phase as revealed by simultaneous global view of auroral activity from IMAGE. We examine the associated Hall current system signature, current density, electric field, Lorentz force, and current dissipation/dynamo term, the last two parameters being new features that have not been studied previously for plasma flow reversals. It is found that (1) there was no clear quadrupole Hall current system signature organized by the flow reversal time, (2) the x-component of the Lorentz force did not change sign while the other two did, (3) the timing sequence of flow reversal from the Cluster configuration did not match tailward motion of a single plasma flow source, (4) the electric field was occasionally dawnward, producing a dynamo effect, and (5) the electric field was occasionally larger at the high-latitude plasma sheet than near the neutral sheet. These observations are consistent with the current disruption model for substorms in which these disturbances are due to shifting dominance of multiple current disruption sites and turbulence at the observing location.

Keywords. Magnetospheric physics (Magnetospheric configuration and dynamics; Magnetotail; Plasma sheet)

1 Introduction

Plasma environment in the Earth's magnetotail has been studied since the early days of the Vela satellites in the late 1960's (see, e.g., Hones, 1973). Plasma flows were inferred from these early measurements even though the plasma detectors and the satellite spin axis orientation were not ideally designed to obtain accurate determination of plasma flow direction. It has been recognized in early substorm research that high-speed plasma flows occur during substorms. The lack of multi-point observations in the magnetotail and the ambiguity in differentiating temporal from spatial variations have posed major obstacles in advancing our understanding of substorm phenomena in the magnetotail. The ISEE-1/2 mission demonstrated the power of multi-point measurements from satellites flying in close formation. Subsequently, the International Solar Terrestrial Physics (ISTP) program has brought the prowess of multi-point magnetospheric observations to the forefront of space research. The Cluster-II mission elevates the capability of ISEE-1/2 and ISTP missions even further by the ability to determine gradients in three-dimensions as well as differentiate temporal from spatial variations. This capability provides valuable constraints in data interpretation on magnetotail dynamics.

It is evident that the new capability of Cluster can help to advance our understanding of substorm phenomena. Several investigations have utilized Cluster to examine substorm phenomena in the tail (e.g., Nakamura et al., 2002; Runov et al., 2003). In this paper, we examine a plasma flow reversal in the magnetotail observed by Cluster on 22 August 2001. Plasma parameters associated with the plasma flow reversal, including the Lorentz force and the current dissipation/dynamo term that have not been investigated before, are studied. These observations are used to evaluate two prominent substorm models that will be tested by the upcoming NASA mission THEMIS. The near-Earth neutral line (NENL) model accounts for this type of plasma flow reversal by the tailward movement of an X-line (Hones, 1979; Baker et al., 1996). The current disruption (CD) model accounts

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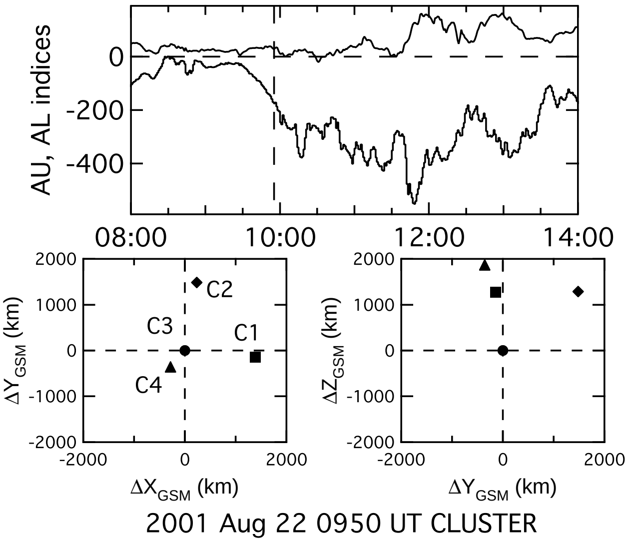

Fig. 1. The AU (upper) and AL (lower) indices on 22 August 2001 and the relative positions of four Cluster satellites in the XY- and YZ-planes in GSM coordinates.

for this type of plasma flow reversal by multiple current disruption sites developing at progressively further downstream distances (Lui, 1991, 1996). It is found that the observed features associated with this plasma flow reversal are consistent with the CD substorm model.

2 Observations

2.1 Overview of activity

The ground-station magnetic activity on 22 August 2001 around the plasma flow reversal interval is shown by the AU/AL indices given in Fig. 1. Within 08:00–14:00 UT, the AL index showed the strengthening of the auroral electrojet signifying substorm development. The plasma flow reversal event studied here occurred during late substorm expansion at the time marked by the vertical dashed line. Cluster satellites were at a downstream location of about (–18.9, –3.4, 0.9) R_E in GSM coordinates at 09:50 UT, i.e., in the midnight sector of the magnetotail. The dimension of the tetrahedron formed by the four Cluster satellites was ∼2000 km, with C3 (SAMBA) at its apex south of the tetrahedron base. Substorm onset seen by the IMAGE/FUV imager was at ∼09:20 UT, with a sizeable auroral bulge developed at ∼09:26 UT. This and the subsequent auroral activity around the flow reversal are shown in Fig. 2.

Cluster crossed the neutral sheet from north to south during this interval, as shown in Fig. 3 with measurements from C3. Shown in the panels are the number density, the ion temperature (red trace), the x- and y-components of plasma flow, the y-components of electric field and $-V \times B$ (cross-product of plasma flow and magnetic field – red trace), the x- and y-components of the magnetic field, and the z-component of the magnetic field. The plasma, electric field, and magnetic field measurements on Cluster were taken by CIS (Rème et al., 2001), EFW (Gustafsson et al., 1997), and FGM (Balogh et al., 2001), respectively. The plasma data used here are from CIS/HIA. The measurements show several dipolarizations of the magnetic field and plasma flow reversals. It also can be noted that the y-components of electric field and $-V \times B$ matched well in general but significant deviations can also be seen intermittently.

2.2 Magnetic signatures and timing sequence of the plasma flow reversal event

There were some large-scale MHD oscillations of the plasma sheet previously studied by Volwerk et al. (2003), Louarn et al. (2004), and Fruit et al. (2004). There was a notable plasma flow reversal from tailward to earthward near the end of the substorm expansion phase at ∼09:54 UT that was not discussed by the previous studies. Figure 4 shows in expanded time scale the perpendicular plasma flow V_x and V_y components from CIS/HIA on C1 (RUMBA) and C3, from CIS/CODIF on C4 (TANGO) (no data from CIS on C2), the magnetic field B_x and B_z components from all four spacecraft. Different standardized colors are used to denote data from different spacecraft, as indicated by the colored labels at the top left corner. In panel (d), the traces are offset for clarity with the corresponding zero level shown. The plasma flow reversal was generally accompanied by a reversal in the B_z component. The signatures of the V_x and B_z in this event are similar to the flow reversal and X-line encounter interval of 09:47–09:51 UT on 1 October 2001 reported by Runov et al. (2003). In particular, there was a period of very low speed flow within the flow reversal interval while the B_z component changed sign from negative to positive.

A quadrupole B_y signature is expected around an X-line (Sonnerup, 1979), i.e., $B_x B_y < 0$ tailward of the X-line (before flow reversal) and >0 earthward of it, valid for both north and south of the current sheet. In order to see this, one may note that tailward of an X-line, $B_y < 0$ north of the neutral sheet ($B_x > 0$) and $B_y > 0$ south of it ($B_x < 0$). Therefore, the product $B_x B_y < 0$ in both north and south of the neutral sheet. Similarly, earthward of an X-line, $B_y > 0$ north of the neutral sheet and $B_y < 0$ south of it. The product $B_x B_y > 0$ in both north and south of the neutral sheet. Thus, the magnetic perturbation associated with the Hall current system can be revealed better by the sign of the product$B_x B_y$, eliminating the confusion introduced by plasma sheet flapping. This product, normalized by the B_x magnitude, is shown in Fig. 5 with the flow reversal time for the corresponding satellite indicated by the arrow below the trace. There are significant deviations from the expected trend. For example, for C1, the parameter was only intermittently negative prior to flow reversal and was definitely positive ∼1 min before the flow

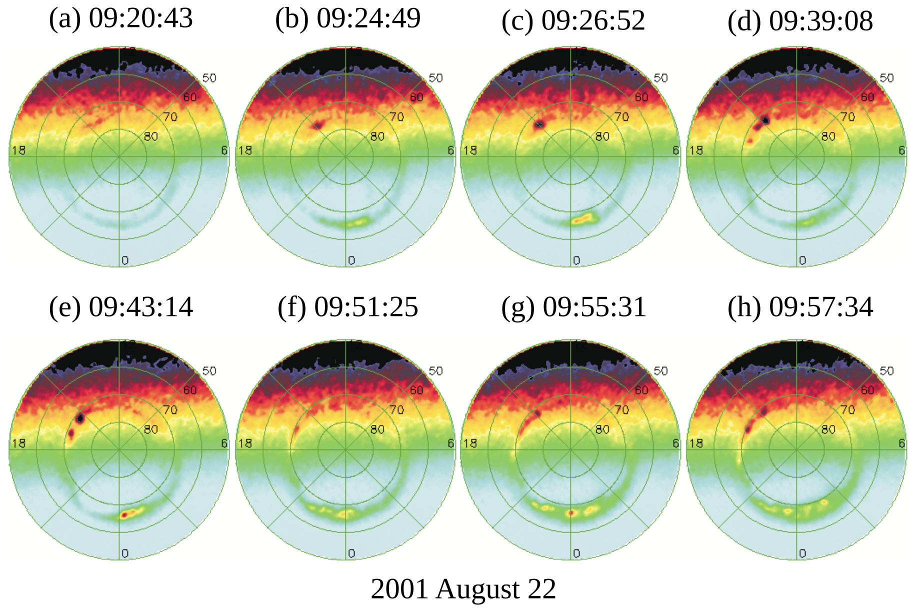

Fig. 2. Global auroral activity from IMAGE/FUV during the flow reversal interval.

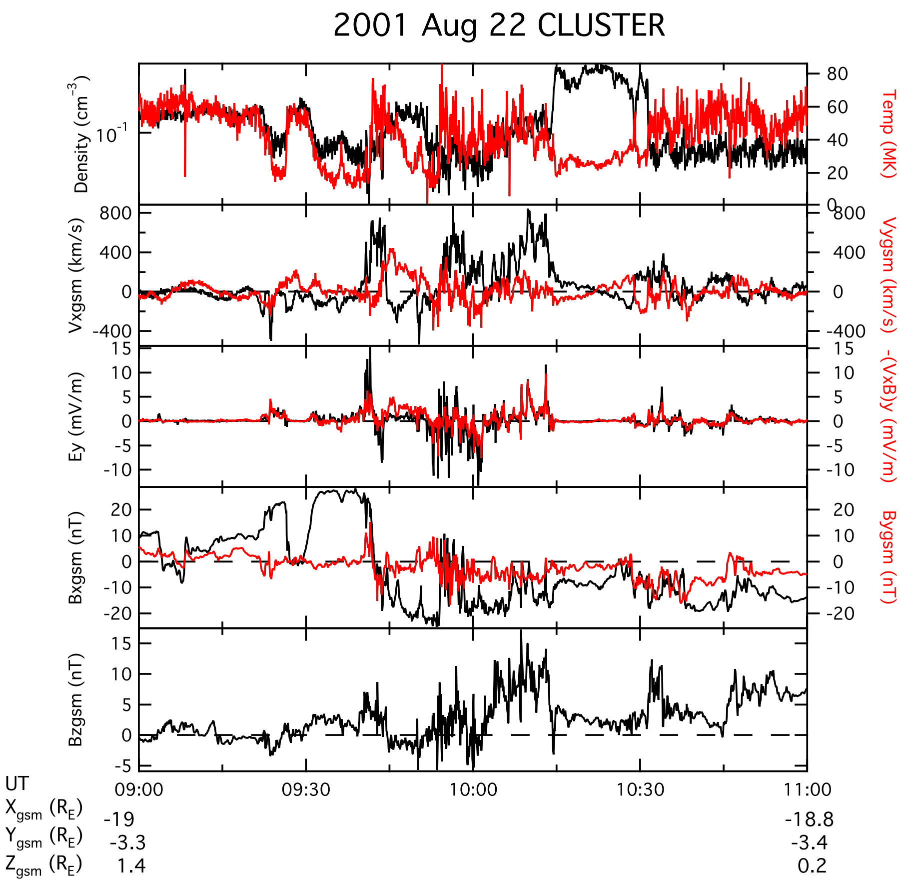

Fig. 3. Overview of Cluster observations during the substorm on 22 August 2001.

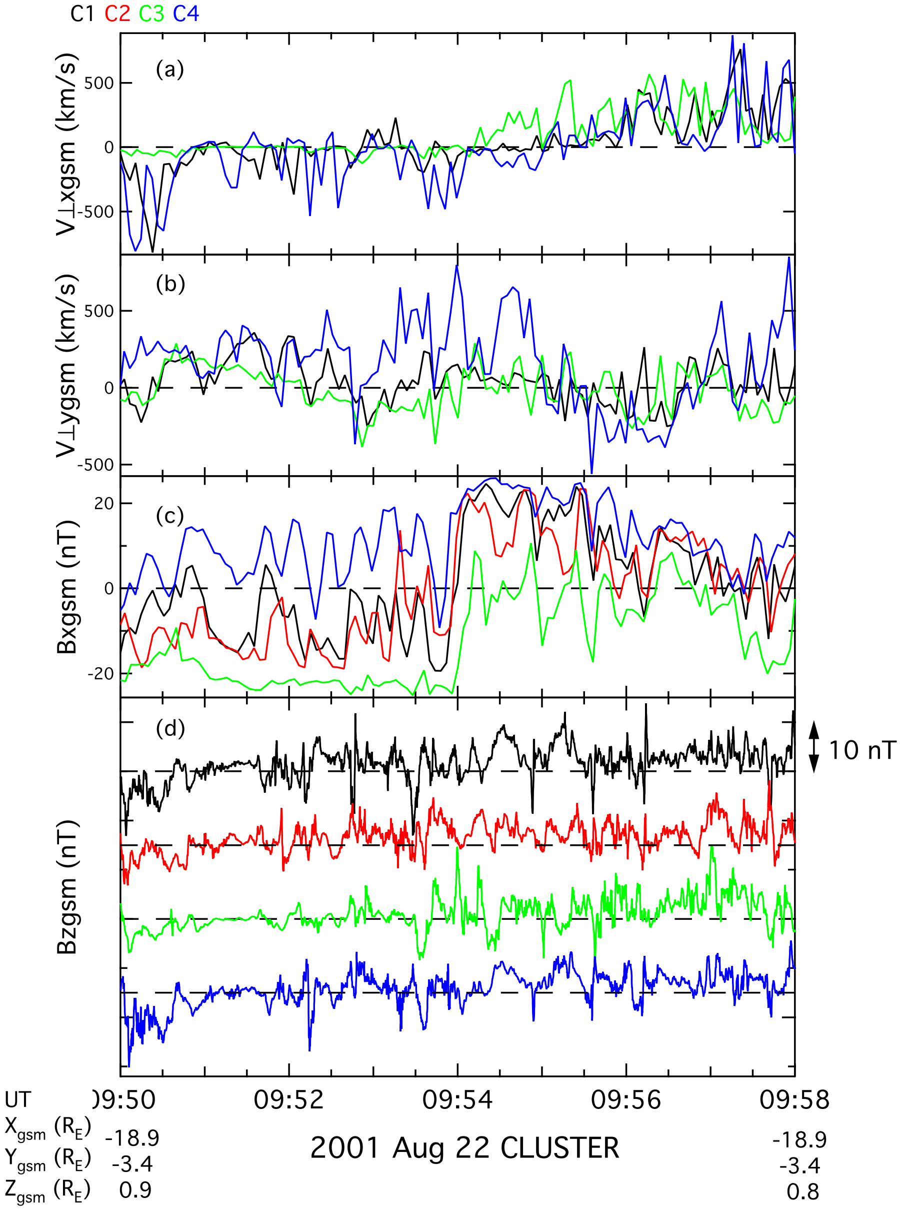

Fig. 4. Cluster observations of plasma flow reversal and the associated magnetic field reversal.

reversal. For C3, the trend was more consistent with expectation, but there were many significant deviations as well. The trend for C4 was similar to C1, with the parameter turning positive nearly 2 min before flow reversal. Also, the expected sequence of flow reversal for a tailward moving plasma flow source based on the X_{GSM} location of the Cluster configuration is C1-C3-C4. The observed time sequence is C3-C1-C4 instead. Although the flow reversal timing is based on CIS/HIA data, we have also examined the CIS/CODIF data and found them to give almost identical timing.

2.3 Current associated parameters during the plasma flow reversal

The parameters associated with current density during the flow reversal interval are shown in Fig. 6. The curlometer technique (Dunlop et al., 1988) is used to determine these parameters. The j_y component stayed positive while the j_x component reversed sign from positive to negative at plasma flow reversal. Interestingly, there was a sign reversal of the y- and z-components of $j \times B$ at flow reversal while the x-component did not show a clear reversal. This indicates that the magnetic stress in the y- and z-directions changed

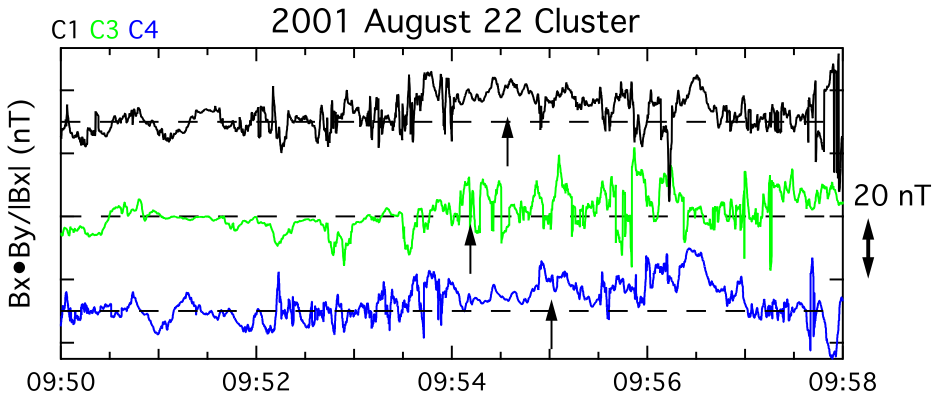

Fig. 5. The paarameter $B_x B_y/|B_x|$ to check for the signature of the quadrupole magnetic perturbation from the Hall current system associated with magnetic reconnection. The arrow below each trace indicates the plasma flow reversal time for that satellite.

at flow reversal but not in the x-direction. The current dissipation/dynamo term $j_y E_y$ was quite variable, indicating the occasional presence of the dynamo effect (negative value) in addition to dissipation (positive value). The electric field component used in this term is the average over the four spacecraft. Furthermore, this quantity is computed in the GSE coordinate system since only two components of the electric field were measured on the GSE *xy*-plane. In this way, we avoid making any assumption on the unmeasured component to infer the three components of the electric field. The computed value of *div* $\boldsymbol{B}$ during this period typically lies within $\pm 5\,\mathrm{nT}/10^3$ km and exceeds $\pm 10\,\mathrm{nT}/10^3$ km only for a few data points (Runov et al., 2003). The above characteristics concerning current-associated parameters would be unchanged even if points with *div* $\boldsymbol{B}$ exceeding $\pm 5\,\mathrm{nT}/10^3$ km were removed. These characteristics are thus not affected by potential inaccuracies in the current density computation.

2.4 Electric field signatures during the plasma flow reversal

Another feature is the observed electric field, which is expected to have a duskward component near an X-line and the highest value closest to the neutral sheet. However, Fig. 7 shows the E_y component (the most reliable component from EFW) was intermittently dawnward (negative), especially at C3, which was generally the closest satellite to the neutral sheet among the four as judged by the magnitude of the B_x component. For instance, during two intervals (09:54:25–09:54:40 and 09:55:10–09:55:20 UT), the electric field was large at C1 where the B_x component was large (i.e., far from neutral sheet) while it was small at C3 where B_x component was small (i.e., close to the neutral sheet).

3 Summary and discussion

3.1 Summary

This study presents detailed examination of a plasma flow reversal event seen by Cluster in the magnetotail during substorm expansion when simultaneous global viewing of auroral activity is available from IMAGE. The analysis includes examination of the Lorentz force $j \times B$ and the current dissipative/dynamo term $j_y E_y$ associated with the plasma flow reversal. These two parameters have not been examined by previous reports of plasma flow reversals. This plasma flow reversal, from tailward to earthward, was accompanied by southward magnetic field component reversing to northward and occurred during the late phase of substorm expansion. Close examination shows several interesting features: (1) there was no clear sign of the quadrupole magnetic perturbations from a Hall current system organized by the flow reversal time; (2) the x-component of the Lorentz force did not change sign at plasma flow reversal although the other two components did; (3) the timing analysis of plasma flow reversal among the Cluster satellites was inconsistent with tailward movement of a plasma flow source; (4) the electric field occasionally was dawnward, opposite to the current density direction and indicative of a dynamo action occasionally; and (5) the electric field occasionally had a larger value far from the neutral sheet than close to it.

3.2 Comparison with NENL model predictions

There are two prominent substorm models, namely, the NENL and CD models, that depict magnetotail disturbances at the late stage of substorm expansion. In the NENL model, plasma flow reversal signifies the tailward retreat of an X-line. More specifically, this model predicts the following signatures: (1) detection of the quadrupole magnetic perturvations from a Hall current system organized by the plasma

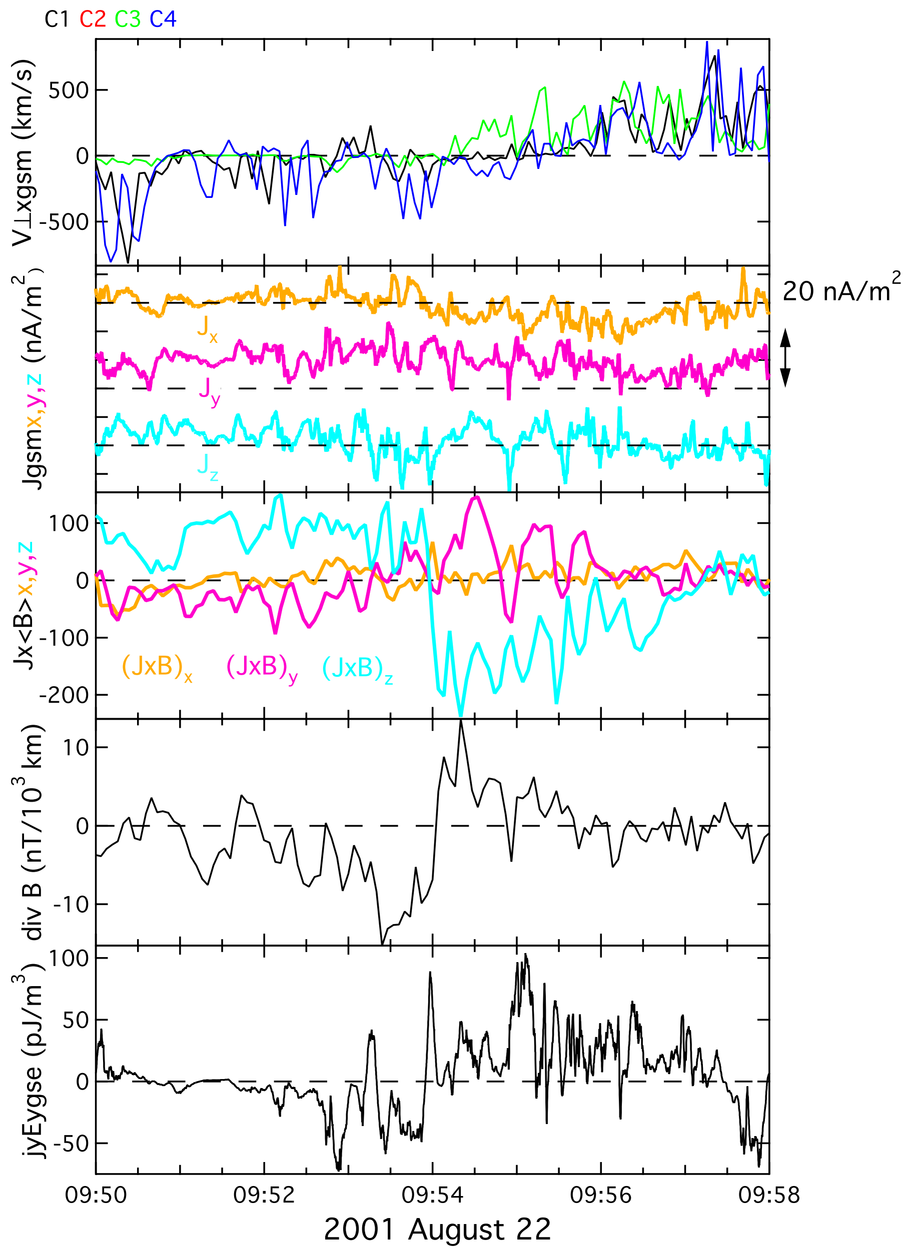

Fig. 6. Plasma parameters associated with current density during the plasma flow reversal. The unit for $j \times B$ components is nT-nA/m^2.

flow reversal time; (2) the x-component of the Lorentz force changing sign simultaneously with the plasma flow reversal; (3) timing sequence of flow reversal at different downstream distances indicating tailward motion of the plasma flow source; and (4) duskward electric field around the plasma flow reversal region in association with dissipation. Four of the five observed features summarized in the Sect. 3.1 are inconsistent with the scenario of the NENL model.

3.3 Comparison with CD model predictions

In the CD model, plasma flow reversal is produced by development of multiple current disruption sites at progressively further downstream distance in the magnetotail. Current disruption is crudely speaking equivalent to generation of a dawnward current. This can produce southward magnetic field tailward of the current disruption site when the ambient magnetic field prior to activity is weak (Lui, 2001), which can lead to tailward plasma flow. No clear signature of quadrupole magnetic perturbations is expected to be

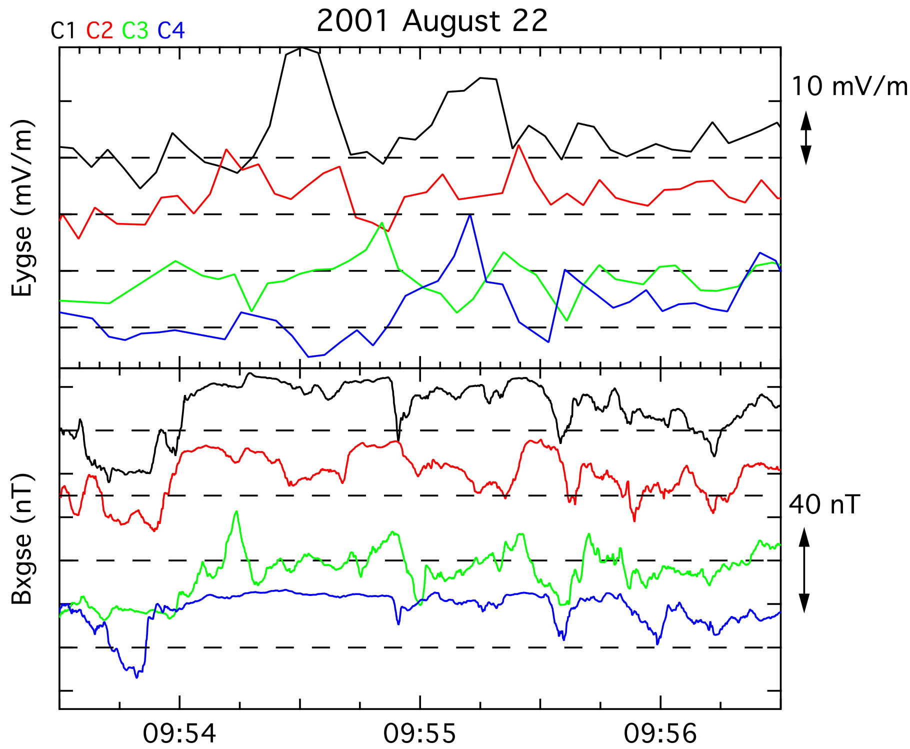

Fig. 7. Comparison between the simultaneous measurements of E_y and B_x from all four satellites during the plasma flow reversal.

organized by the flow reversal time from this scenario. The x-component of the Lorentz force is highly dependent on the turbulent distributions of the current density and the B_z component resulting from the nearby current disruption sites and is thus not expected to have an orderly pattern. The change in the y- and z-components of the Lorentz force suggests that the dominant activity site shifted from duskward to dawnward of Cluster and from below to above Cluster. This shift is entirely consistent with the expected dawnward expansion of substorm activity. Indeed, the auroral activity seen by IMAGE/FUV indicates that a new activity site developed at ∼09:53 UT to the east of the existing activity site. The new activity site intensified at ∼09:55 UT (Fig. 2g) and the old activity site faded away at ∼09:57 UT (Fig. 2h). In addition, from the ion velocity distribution measured by CIS/HIA on C3, there was another ion population flowing duskward in the interval (09:54–09:55 UT) when the plasma flow reversed (note the positive V_y during this time in Fig. 4b). This feature is also consistent with another plasma flow source developed to the dawnside of Cluster. Furthermore, the centroid of the Cluster tetrahedron moved from south of the neutral sheet to north of it, consistent with the expected change in the z-component of Lorentz force that points toward the neutral sheet. The changing direction and the variable strength of the electric and magnetic fields are expected from turbulence arising from current disruption (Lui et al., 1988), which can give rise to dawnward electric field and dynamo effect, distinct from magnetic reconnection where only duskward electric field and dissipation are expected. Current disruption in the two-dimensional particle simulation of a thin current sheet exhibits current filamentation and fluctuating electric fields as well as current sheet bifurcation (Figs. 31 and 32 in Lui, 2004). The instability is tentatively identified as the cross-field current instability (Lui et al., 1991; Yoon et al., 2002). The simulation result is reproduced here in Fig. 8. Further tests of the CD substorm model and the NENL model will be made by the upcoming NASA mission THEMIS.

3.4 Comparison with an X-line encounter reported previously

For comparison purposes, we have also examined the observations of flow reversal event documented by Runov et al. (2003). They have demonstrated well the existence of the quadrupole magnetic perturbations for their event. We have found that the z-component of the Lorentz force in their event was the largest component and was directed toward the neutral sheet, similar to the event reported here. However, the x-component of the Lorentz force was directed earthward during tailward flow and reversed to tailward directed during part of the earthward flow interval. This behavior of the x-component of the Lorentz force is opposite to the expected directions for the reconnection configuration. In addition, the timing sequence of plasma flow reversal from tailward retreat of an X-line based on the X_{GSM} location of satellites

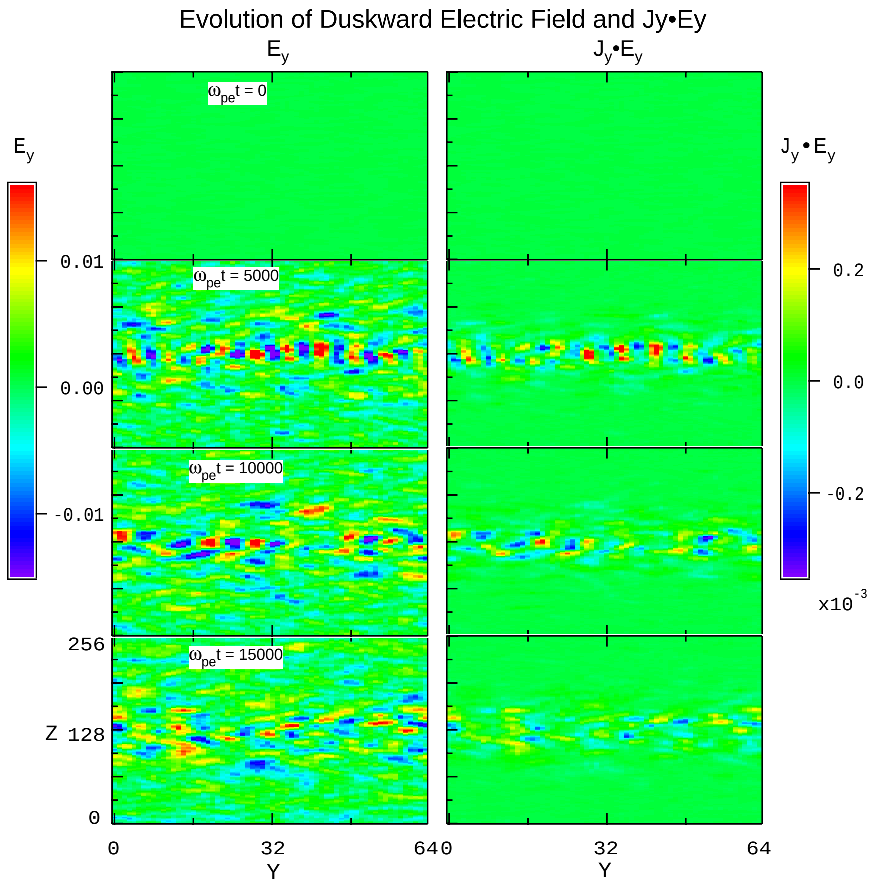

Fig. 8. Evolution of current density and the current dissipation/dynamo term in 2-1/2D particle simulation of current disruption (Lui, 2004). Each panel shows a *yz*-plane cut of the current sheet. As time progresses, the initial relatively uniform current density breaks up, exhibiting both dissipation ($j_y E_y > 0$) and dynamo effect ($j_y E_y < 0$).

should be C3-C1-C4 while the observed sequence is C3-C4-C1. Furthermore, the electric field was directed dawnward intermittently during the flow reversal interval accompanied by negative $j_y E_y$ term, i.e. dynamo effect. The electric field occasionally became larger at the high latitude of the plasma sheet than near the neutral sheet, as reported by Cattell et al. (2005) and Wygant et al. (2005) for this event. Cattell et al. (2005) used the burst mode data to propose the detection of electron holes near the plasma sheet boundary as a feature consistent with magnetic reconnection. Wygant et al. (2005) considered the tilting of the current sheet in the *yz*-plane, a wavy profile of the current sheet first discovered by Lui et al. (1978), to relate the E_y component with the electric field normal to separatrix surface in the reconnection plane. In their analysis, the E_y component plays a pivotal role in particle acceleration and thus should be associated with dissipation. The occurrence of negative $j_y E_y$ is therefore unexpected. Therefore, not all the observed features in the 1 October 2001 event are consistent with tailward retreat of an X-line.

3.5 Concluding remarks

It is unclear how general the above findings are for plasma flow reversals. More events will be examined in the future. However, at the very least, this report demonstrates that for this event, plasma flow reversal from tailward to earthward accompanied by magnetic field reversing from southward to northward, is consistent with multiple current disruption sites dominating a given observation point as envisioned by the current disruption substorm model.

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