TAIL RECONNECTION AND PLASMA SHEET FAST FLOWS

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ABSTRACT

The present state of understanding the process of tail reconnection and plasma sheet fast flows obtained from Cluster measurements is reviewed. Being a constellation of four identical spacecraft, Cluster allows discrimination of spatial and temporal variations in magnetic field and plasma parameters. Thus it is ideal to study the structure and dynamics of plasma and fields relevant to reconnection, which is a highly dynamic system. Observations of current sheet crossings near the X-line obtained the geometry of reconnection region and confirmed the effects of unmagnetized ions including the Hall-current and its closure currents. Cluster multi-point observations identified three dimensional structures and dynamics of the fast flows in the plasma sheet, which could be ascribed to the localized and/or temporal features of the reconnection region.

Key words: Cluster, reconnection, magnetosphere, plasma sheet.

1. INTRODUCTION

Whereas the dayside magnetosphere is compressed by the solar wind, the nightside magnetosphere is stretched out into a long magnetotail. When the interplanetary magnetic field (IMF) is southward, the merged field lines at the dayside are transported toward the nightside, reconnected in the distant tail and then transported back toward the dayside, creating inward and Earthward flow in the central plasma sheet. The flux transport rates at the dayside and at the nightside are, however, balanced only in an average sense and the unbalanced transport is the ultimate cause of a substorm when magnetic reconnection takes place closer to the Earth, at radial distances of 15 - 30 R_E in the tail. The processes associated with this near-Earth reconnection determine different scales of magnetotail dynamics.

High-speed plasma flows in the near-Earth and the mid-tail plasma sheet are considered to play a key role in flux and energy transport in the magnetotail. These fast flows are considered to take place as a consequence of reconnection. The flows near the boundary of the plasma sheet consist of field-aligned beams, whereas the flows in the central plasma sheet tend to have a large bulk-flow component. The latter flows organize themselves in 10-min timescale flow enhancements, which are called bursty bulk flow (BBF) events, embedding velocity peaks of 1-min duration, which are called flow bursts, and have characteristics distinctly different from plasma sheet boundary layer flows (1; 2).

Cluster traversed the magnetotail covering regions Earthward of 19 R_E during the past four summer seasons since July 2001. The tetrahedron scale was between 250 km and 4000 km, which were changed every year, so that characteristics at different scales could be identified. The four spacecraft observations enable us for the first time to differentiate spatial from temporal disturbances. Here we highlight several Cluster observations near the X-line, remote observations from X-line but showing the effects of the processes in the ion diffusion region, and temporal and spatial structure of the plasma sheet fast flows to discuss more global context of the reconnection based measurements from the Cluster tail season in 2001 and 2002.

2. OBSERVATION OF X-LINE SIGNATURES

The four spacecraft observations enable us to obtain spatial gradient of different parameters continuously. For example, the current density obtained from the gradient in the magnetic field is an essential parameter for magnetotail diagnostics. Fig. 1 shows repeated current sheet crossings interval near a flow reversal observed on October 1, 2001 from (3). Cluster observed a fast flow reversal from tailward, with a maximum speed of 800 km/s, to Earthward, with maximum value of 700 km/s. The magnetic field curvature vector, calculated from four-point magnetic field observations also reverses, first pointing tailward during the tailward flow, then Earthward during the Earthward flow. The corresponding reversals of the magnetic field curvature and proton bulk velocity indicate that Cluster crosses the magnetic X-line, travelling tail-

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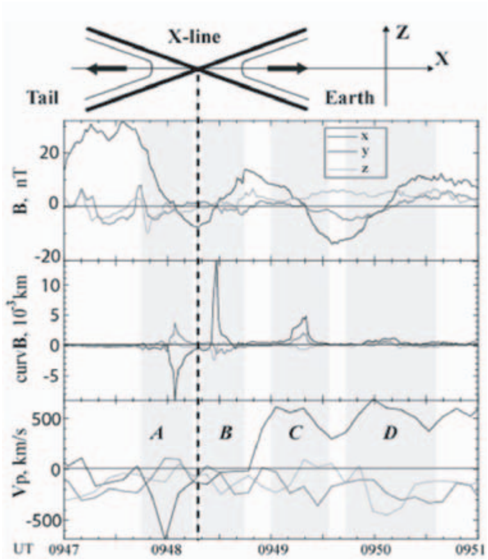


Figure 1. October 1, 2001: Magnetic field at Cluster barycenter from FGM, components of $\mathbf{C} = (\mathbf{b} \cdot \nabla)\mathbf{b}$, and the proton bulk velocity from CIS during flow reversal events. Thickest lines show the X component which is discussed in the text.(from (3))

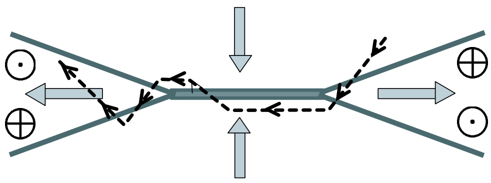


Figure 2. Sketch of Cluster observations of Hall magnetic fields and current sheet structure around the reconnection region; the red dashed line indicates the trajectory of Cluster (Adapted from (3)).

ward (3). Using the gradient information obtained from the four Cluster spacecraft during current sheet crossings, current sheet structures in the vicinity of X-line were reconstructed by (3) as illustrated in Fig. 2. A thin current sheet with a half-thickness of about one ion gyro radius was found for the crossing closest to the X-line, whereas the outer crossings showed bi-furcated current sheet profiles. Changes in the curvature of the field for the different current sheet crossings illustrated in the figure were consistent with a X-line motion from Earthward and tailward of the spacecraft. Furthermore, consistent feature of the field disturbance associated with Hall-current at both side of X-line were identified, confirming that the spacecraft traversed the ion diffusion region.

New signatures have been further studied for the reconnection event on October 1, 2001. The importance of multi-scale processes from heavy ions to electron kinetics in the reconnection processes have been identified by several Cluster observations. During thin current sheet intervals associated with crossings of the X-line during storm-time substorms, the O^+ pressure and density were observed to be dominated compared to those of H^+ (4). In such current sheets, the O^+ were observed to execute Speiser-type serpentine orbits across the tail and were found to carry about 5-10% of the cross-tail current (4). The O^+ in the reconnection region was suggested to experience a ballistic acceleration (5) based on the observation of a large amplitude bipolar electric field. These large-amplitude (up to 50 mV/m) solitary waves, identified as electron holes, have been observed during several plasma sheet encounters that have been identified as the passage of a magnetotail reconnection X-line (6) The electron holes were seen near the outer edge of the plasma sheet, within and on the edge of a density cavity, at distances on the order of a few ion inertial lengths from the center of the current sheet. Based on detailed comparison with simulation (6) suggested that the observed nonlinear wave mode, electron holes, may play an important role in reconnection by scattering and energizing electrons.

3. EFFECTS OF X-LINE(S)

Whereas in situ observations of ion diffusion region depend on the rare chance that the spacecraft being located at the right place at the right time, different effects of reconnection can be detected remotely from the reconnection site and can still contain useful information on temporal and spatial characteristics of reconnection. For example, the limited area of the Hall currents flowing in the ion diffusion region indicates that the current has to be closed including regions outside of the ion diffusion region. At the lobe side, the closure of the Hall current takes place via cold electron flowing into the ion diffusion region. At the outflow region, on the other hand, the accelerated electrons can carry the current into the ion diffusion region. Cluster observed such field-aligned electrons related to the Hall current system consistent with previous observations, but also obtained fine structures indicating multiple temporal or spatial properties of reconnection (7; 8; 9). Fig. 3 illustrates multi-point observations by Cluster in the northern hemisphere and by Geotail in the southern hemisphere detecting these field aligned currents possibly connected to the ion diffusion region from (7). Cluster four spacecraft also allowed to determine the scale size of these field aligned currents which suggested that the scale size of the downward current was at maximum comparable to the ion inertia length so that it plausibly connects to the near-Earth X-line and is driven by Hall effects in the reconnection region. This interhemispheric observation supported the theoretical prediction (10) that the downward current region is thin because on the lobe side, the ions may travel a substantial fraction of the ion inertia length until their motion separates from that of the electrons.

Using multi-composition plasma observation by Cluster, slow-mode shocks connected to the ion diffusion region have been analyzed by (11) taking into account also the contribution from the oxygen during a substorm X-line event when Cluster observed fast tailward and Earthward flows. The successful joint Walén and slow shock analyses on the tailward flows within the plasma sheet

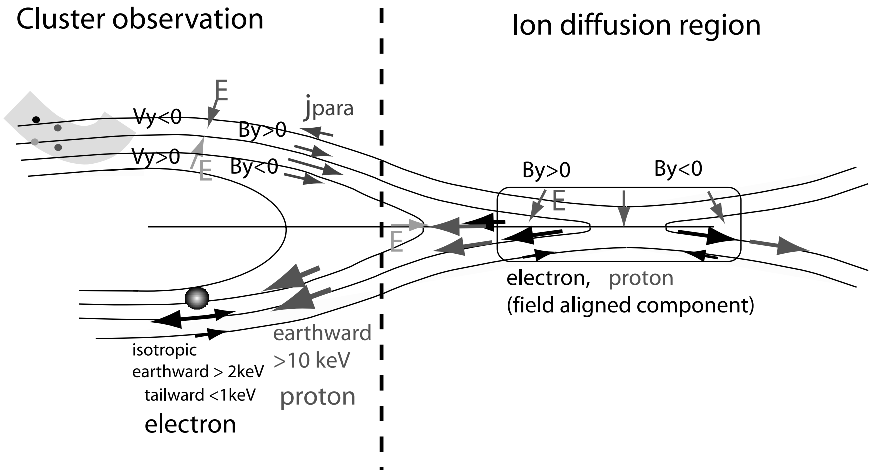


Figure 3. Summary of observations by Cluster and Geotail during a transient entry into the plasma sheetd during a substorm event and illustration of the possible relationship to the reconnection region. For Cluster observations field signatures are showing in the northern hemisphere, while particle signatures are illustrated in the southern hemisphere; adapted from (7).

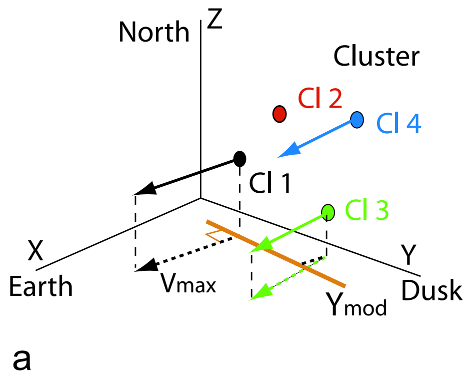
presented further evidence in favor of Petschek-type reconnection at distances X_{GSM} $>$ -19 R_E of the near-Earth magnetotail.

Cluster succeeded to obtain detailed characteristics of earthward propagating southward then northward magnetic field disturbances related to plasmoids/flux rope (13; 14), traveling compression region (15; 16) and nightside flux transfer events (12). Multi-point analysis by Cluster were used to measure the current density and check the force-free model (15) and energetic particle boundaries (14) to show the structures of the plasmoid/flux rope. Yet, since the plasma flow jetting toward the Earth is significantly influenced by the strong dipolar field and pressure gradient, it still remains unknown to what extent these structures can be treated as motions of a stable structure in the analysis. As described in the later sections, similar magnetic features were rather interpreted as transient profiles of a remote X-line due to its change in the reconnection rate and used to determine the location of the X-line (12). Observationally, determination of the field topology would be a key to differentiate whether these structure are coming from a single X-line or signature of multiple X-lines.

4. SPATIAL SCALE AND STRUCTURE OF THE PLASMA FLOW

In the plasma sheet, bursty bulk flows (BBF) are the most clear signatures of the consequence of reconnection and have been intensively studied by Cluster spacecraft based on multi-point data analysis. Using proton flow data from the Cluster 1, 3 and 4 spacecraft, that have identical plasma instruments, the gradient scale of the flow was obtained by (17). Note that there are no ion data from Cluster 2. Data used in their study are obtained between July and October 2001, when the satellite was in the midtail $X_{GSM} < -15R_E$ plasma sheet ($\beta_{XY} > 0.5$, where XY corresponds to X and Y components of the magnetic field used for the calculation) and at least one of the spacecraft observed a BBF, which were selected using the following condition: plasma $\beta_{XY} > 2$, and $V_{\perp XY} > 300$ km/s, where $V_{\perp XY}$ is the equatorial component of the flow perpendicular to the magnetic field. Due to Cluster's apogee at 19 R_E and the condition in X and in plasma β, the location of the events was restricted to the night-side equatorial region, i.e., $|Y| < 11R_E$ and $-4 < Z < 6R_E$. Since only 22% of the flows were directed tailward, statistical analysis was performed only for Earthward flows $(V_{\perp X} > 0)$.

In order to determine the spatial change of the high-speed flow, the maximum flow was compared with the flows obtained by the other two spacecraft for each event. Although the plasma sheet flow direction observed by Cluster was centered around Earthward, a significant portion of the flows had an azimuthal component. Therefore the direction of the maximum flow was used as reference for gradient determination as is illustrated in Fig. 4a. Fig. 4b shows the distribution of the spatial gradients of high-speed flows which were estimated using a combination of two-point observations from the Cluster spacecraft along the "dawn-dusk" direction (perpendicular to the main flow and in the plane of the tail current sheet), indicated as the Y_{mod} direction. The average and median of the spatial gradients, which were 0.17 [/1000 km] and 0.13 [/1000 km], respectively, indicate that the full width of the flow channel is 2-3 R_E in the "dawn-dusk" direction assuming that the flow channel has a linear gradient. This is a comparable value to the previous estimates. The velocity gradient at the duskward edge of a flow tends to



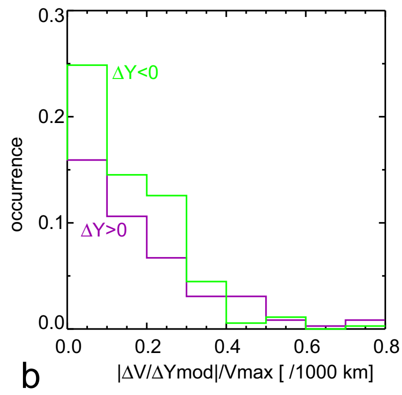


Figure 4. (a) Schematic to show the relationship between the GSM X and Y direction and Y_{mod} in the modified coordinate system referring to the direction of the fast flow. In this drawing, BBF is fastest at Cl 1 and is compared with the flow obtained by Cl 3. (b) Histograms showing the occurrence of the rate of change in the flow speed in Y_{mod}, the 'adapted' dawn-dusk direction. The occurrence numbers are normalized by the total numbers (358) of events given at the top of the panel. The rates are normalized for a distance of 1000 km. The light line is for the dawnside edge of BBF, whereas the dark line is for the duskside edge of the BBF values (adapted from (17)).

be sharper than that at the dawnward edge, possibly reflecting an asymmetry in the magnetosphere-ionosphere coupling process associated with the flow. More details including the results on the north-south scale are given in (17).

When the Cluster tetrahedron scale was about 4000 km in summer 2002, it was suitable to observe the spatial structure of the bursty bulk flows. An isolated flow burst example observed around 2202 UT on September 1, 2002, shown in Fig.5, was studied by (18). Earthward flow with a speed exceeding 700 km/s with a perpendicular component up to 600 km/s was observed between 2202 and 2204 UT associated with a sharp enhancement in B_Z, indicating dipolarization. The flow burst was associated with a decrease in density and increase in magnetic field pressure (not shown), which is a typical signature for a plasma bubble (19). Both the flow and the magnetic field traces showed time differences among the spacecraft. That is, the dipolarization started at Cluster 4, followed by Cluster 1 and 2, and then Cluster 3. Note that Cluster 4 was located most tailward, as shown in Fig.5f and 5g. Cluster 3 was located about 3000 km south of the other three spacecraft. Thus, the disturbance in dipolarization was propagating toward Earth and toward the equator.

The structure of the fast flows were further determined by examining the orientation of the dipolarization front by performing minimum variance analysis of the magnetic field in the same way as (19). The shape of the dipolarization front is expected to reflect the spatial structure of the fast flowing plasma. The orientation of the dipolarization front of the three northern spacecraft, Cluster 1, 2, and 4, shows a clear dependence in Y direction (Fig.5f), while Cluster 3 was located away near the neutral sheet and detected a somewhat different behavior. The dipolarization front of Cluster 2, which is located most duskward, is more tilted toward the X direction compared to Cluster 1 and 4, which have a dipolarization front more aligned in the Y direction. The difference suggests that Cluster 2 sees the edge effect of a localized flow channel. If we simply assume a dipolarization front with an elliptical shape in the X-Y plane, the dimension of the front, and therefore the spatial scale of a flow channel, is estimated to have a width of about 3 R_E, consistent with the typical scale of a flow burst.

Fig.5g shows that the dipolarization was propagating toward Earth and toward the equator and the dipolarization front is oriented so that it forms a concave shape in the X-Z plane in contrast to the convex shape in the X-Y plane. Fig.5f and 5g suggest that the most likely shape of a BBF is that of a localized localized flux-tube. Such distribution of the flows is consistent with the model of the BBF by (20). Furthermore, using Cluster, together with the other spacecraft and ground-based observations, BBF-associated field-aligned and ionospheric current system have been obtained (21; 18).

5. SUMMARY

The four Cluster spacecraft enabled to identify signatures in the reconnection region due to Hall-physics, effect of multi-composition plasma and electron physics by simultaneously monitoring the scale of the current sheet (structure in Z direction). Further detailed comparison with theory is ongoing. Here, one of the challenging task is to understand the signatures of reconnection also in time domain with knowledge of the spacecraft location relative to X-line (in X direction). Remote observations of flow/field disturbances are shown to reflect temporal and/or spatial characteristics of reconnection.

Cluster observations also enabled to identify several im-

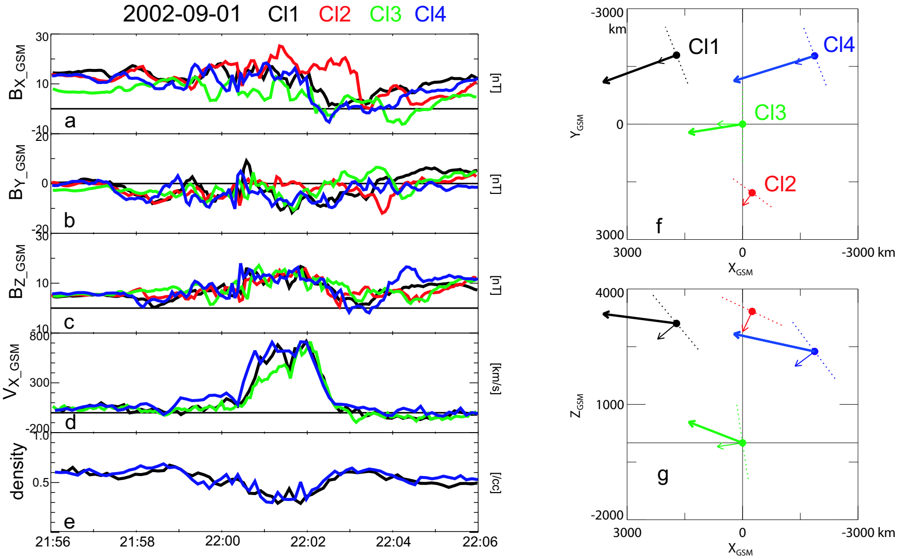


Figure 5. Cluster observation of (a) X, (b) Y, and (c) Z component of the magnetic field, (d) X component of the ion flow, (e) proton density between 21:56 and 22:06 UT. Location of the four Cluster spacecrafts relative to the reference spacecraft (Cl 3) in (f) the GSM $X-Y$ plane and (g) the $X-Z$ plane. The dotted lines show the projection of the dipolarization front described in the text. The thick arrows are the plasma flows at the interval of maximum flow speed while the thin arrow indicates the normal direction to the dipolarization front (from (18)).

portant characteristics of the fast flows using multi-point data analysis techniques. Based on statistical studies of the spatial gradient of the flows and event studies analyzing the dipolarization front, the spatial scale of plasma sheet fast flows was determined from multipoint observation. In terms of current sheet configuration change associated with plasma sheet fast flows, there are two types of fast flows: those related to dipolarization and those associated with current sheet thinning. Large current density intervals are more likely to have fast flow events. Evidences are shown that field aligned current is associated with the flow burst. These observations are consistent with the the plasma bubble model, in which a plasma depleted structure is jetting out from a locaized and/or transient reconnection region.

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