Substorm expansion onsets observed by Cluster

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Abstract. In this paper we study plasma and field signatures in the magnetotail by analyzing Cluster data during intervals with multi-onset auroral substorms between 16:00 and 19:00 UT on August 12, 2001. The Cluster spacecraft, with their high-inclination orbit, traversing from the northern lobe to the plasma sheet, encountered substorm disturbances at several different locations. These include changes in lobe convection, plasma sheet thinning and expansion, and associated high speed flows. Using data from the four spacecraft, we determine the temporal and spatial scales of these substorm disturbances.

1. Introduction

Between early July and early November 2001, Cluster traversed the magnetotail, covering regions Earthward of 19 \textit{R}_E. The four spacecraft observations enable us to differentiate spatial from temporal disturbances and provide a chance to obtain essential parameters, such as current density or spatial scale of the flow and field disturbances unambiguously and continuously. Such parameters were obtainable before only under limited condition with a single spacecraft or from fortuitous multi-point observations. In this paper, we present magnetic field and plasma properties obtained by Cluster during auroral substorms between 16:00 and 19:00 UT on August 12, 2001. We highlight observations of the disturbances near the plasma sheet boundary layer (PSBL) and near the neutral sheet associated with substorm expansion and discuss its spatial scales.

2. Overview of August 12 substorms

Between 15:30 UT and 19:00 UT, global changes of the aurora were continuously monitored by the Far Ultraviolet (FUV) instrument (Mende et al., 2000) onboard the IMAGE satellite. FUV observes the aurora during a period of 5-10 sec during every 2 minute spin period. There were three auroral
Substorms identified in the data. Figure 1 shows images from the Wideband Imaging Camera (WIC) of FUV during six sequences of the auroral substorms when the intensification and the poleward expansion took place involving the Cluster local time sector. The cross in the figure shows the estimated foot point of the satellite from T89 model.

The first auroral brightening identified at 16:33:33 UT (image not shown) around 23.6 MLT was a localized activation. We looked also into the Kakioka Pi 2 onset data base (Nose et al., 1998) between 16 and 18 UT, during which the station was in the postmidnight sector (1-3 LT) near the local time sector of Cluster. There was a Pi 2 onset at 16:37 UT identified at Kakioka, most likely related to the localized auroral brightening. Westward expansion of aurora was detected at 16:41:44 UT (image not shown) accompanied by a Pi 2 onset at 16:43 UT. A major onset of the first auroral substorm, detected at 16:50 UT in Kakioka Pi2, took place and this activation can be seen in the 16:51:58 image (Figure 1a) centered at 1.2 MLT. Poleward and eastward expansion of the aurora toward the Cluster local time sector can be seen in the 16:58:06 UT image (Figure 1b).

The second auroral substorm started again centered in the premidnight sector (23 MLT) as shown in the 17:34:57 image (Figure 1c). A major activation took place at post midnight sector, as can be identified in the 17:47:14 image (Figure 1d). This activation was detected in the Kakioka Pi2 data at 17:44 UT.

The third auroral substorm was first detected in the 18:38:25 image (Figure 1e) at 0.5 MLT as indicated by the arrow. Poleward and eastward expansion of aurora can be identified in the 18:44:33 UT image (Figure 1f). The time scale of this activation was quite short so that it weakened already by 18:46 UT (not shown).

The Cluster orbit data between 15:00 and 20:00 UT are shown in Figure 2 together with the relative location of the four spacecraft in the (c) X-Y and (d) Y-Z plane, in Geocentric solar magnetospheric (GSM) coordinates. SC 1, 2, 3, and 4 are marked by rectangle, diamond, circle, and triangle, respectively.

The Cluster orbit data between 15:00 and 20:00 UT are shown in Figure 2 together with the relative location of the four spacecraft in the X-Y and Y-Z plane, in Geocentric solar magnetospheric (GSM) coordinates. SC 1, 2, 3,
Cluster was located near apogee (19.4 RE) in the postmidnight sector (0130 MLT) approaching the equatorial plane from the north. While SC 1, 2, and 4 are distributed in a plane nearly parallel to X-Y plane, SC 3 is located about 1500 km south of this plane, leading the other three satellites on their traverse from the northern to southern lobe.

Cluster observations during the three auroral substorms are summarized in Figure 3, which shows the spin-resolution (4-sec) data from the fluxgate magnetometer (FGM) experiment [Balogh et al., 2001] and from the Hot Ion Analyser (HIA) of the Cluster Ion Spectrometry (CIS) experiment [Reme et al., 2001]. The two traces in each plot are from SC 1 (solid curve) and 3 (grey curve). As is expected from the four-spacecraft relative location, the other two satellites, SC 2 and 4, detected similar profiles as SC 1. All the parameters are shown in GSM coordinates. The vertical dotted lines show the different substorm activities obtained from auroral intensification obtained from the FUV/IMAGE as described before.

Cluster traverses from the northern to the southern lobe between 1500 and 2000 UT when the three auroral substorms take place. The large field value in the lobe is likely due to the high solar wind pressure after around 1140 UT, estimated from upstream solar wind data obtained by WIND and ACE. Around 1605 UT the lobe field observed by Cluster increased up to 45 nT, which is consistent with a sudden enhancement in the solar wind dynamic pressure. IMF Bz stayed mainly southward during the whole interval.

During the first auroral substorm, when a substorm with multiple onsets occurred, Cluster entered and exited the plasma sheet boundary layer starting at 1652 UT. In association with the Pi 2 onset at 1700 UT, which is the last one among the four Pi 2 onsets during this substorm and is an onset of poleward and eastward expansion of aurora, Cluster encountered the plasma sheet, most likely due to the plasma sheet expansion, and stayed in the plasma sheet for the next 20 min. High-speed Earthward plasma flow was observed during the expansion of the plasma sheet. The flow is more prominent in the central plasma sheet, which can be seen from the early enhancement of the flow observed by SC3 (grey trace), i.e., the SC located southward and therefore encountering the central plasma sheet earliest.

Cluster gradually returned to the northern lobe before the second onset of the auroral substorm at 17:33 UT. Similar to the previous auroral substorm, Cluster encountered the plasma sheet at 17:47 UT accompanied by high-speed Earthward plasma sheet flow when auroral activity expanded to the postmidnight sector. After returning back to the lobe at 17:57 UT, Cluster re-entered the plasma sheet around 18:03 UT and stayed in the plasma sheet until the end of the period.

In association with the third auroral onset, at 18:38 UT, high-speed Earthward flow was
observed by Cluster accompanied by neutral sheet crossings. The differences between the $B_x$ traces of SC 1 and 3 suggests that a strong gradient in the field was observed during the interval.

To summarize the Cluster observations, plasma sheet encounters of the satellites initially located in the lobe was the main signature for the first two auroral substorms starting at 16:52 and 17:32 UT, while Cluster was in the plasma sheet and observed high-speed flow for the 18:38 UT event. In all these events, it can be seen in Figure 3 that the two traces are more separated during the active periods, which indicates that more localized/transient features become important during the active times. In the following we will discuss in more detail on the plasma sheet response to the 1652 UT and 1838 UT onsets.

3. 1652 onset: Lobe convection and motion of the plasma sheet boundary

As described in the previous section, Cluster was initially located in the lobe and entered and exited the plasma sheet boundary layer associated with multiple Pi 2 and auroral intensifications, until all the four satellites entered the central plasma sheet around 1714 UT. Figure 4 shows the field and particle data between 1646 and 1708 UT, during the time of major activation. Magnetic field from FGM and ion flow from CIS/HIA are shown for SC 1 (solid curve) and 3 (grey curve). For the ion flow data components perpendicular to the ambient magnetic field are plotted. The drift velocity of 1-keV electron obtained from the Electron Drift Instrument (EDI) [Paschmann et al., 2001] for SC 1 are shown in the bottom two plots. The four bars shown in the bottom two panels indicate the velocity of the electron plasma sheet boundary obtained from a timing analysis of the density changes at the plasma sheet boundary using data from the Plasma Electron and Current Experiment (PEACE) [Owen et al., 2001] on all four spacecraft. Here the boundary is assumed to be planar and to move with a constant velocity. The solid vertical lines indicate the Pi 2 onsets, whereas the dashed vertical lines correspond to the two instances of FUV/IMAGE data shown in Figures 1a and b, i.e., around the major onset and when the aurora expanded poleward.

![Figure 4](image)

Figure 4. Field and particle data from Cluster during Pi 2 activation (solid line) and auroral brightening (dotted line) of the first auroral substorm. Magnetic field data from FGM and ion flow from CIS/HIA are shown for SC 1 (solid curve) and 3 (grey curve). The electron drift velocity from EDI for SC 1 is shown in the bottom two panels. The electron boundary motion deduced from PEACE is shown by the horizontal bars in the bottom two panels.

All the four Cluster satellites were located in the lobe, observing a gradual increase of the field until the major auroral and Pi 2 onset. During this interval, the motion of the plasma determined from the ion instrument as well as the electron drift experiment was directed southward and duskward, which corresponds to inward convection toward the center of the tail with 40-50 km/s. Associated with the Pi 2 onset, however, the north-south component of the flow changes toward north and then turns south reaching 100 km/s. The decrease in $B_x$ and the increase in the elevation angle suggests a dipolarization or recovery from a stretched configuration. SC 3 detected a larger decrease
in $B_X$, suggesting that SC 3 dived deeper into the PSBL. The general profile of the flow and field disturbance in the $Z$ direction are similar between the two SC, except for the larger amplitude observed by SC 3. On the other hand, the difference between the two SC is more significant in the $Y$ component of the field and flow disturbances. SC 1 observed enhancement in duskward flow, whereas SC 3 observed dawnward flow.

Similar responses in magnetic field and plasma data can be seen associated with the next Pi 2 onset, except that the whole disturbances involved a region deeper inside the PSBL where stronger Earthward flow was observed (see Figure 3). During this interval, the $Y$ and $Z$ components of the flow were mainly convection of the lower energy plasma, while the Earthward flow was mainly due to a field-aligned beam. Similar to the previous Pi2 onset, enhancements in the southward flow are observed for both satellites, whereas duskward and dawnward flow was observed for Cluster 1 and 3, respectively.

By comparing the motion of the boundary determined from PEACE and the plasma motion determined from EDI and CIS, we can examine whether the plasma moved across the boundary. It can be seen that the northward motion observed in the plasma (ion flow and electron drift) is consistent with the boundary motion, while southward motion of the plasma exceeds the boundary motion, in particular for the second disturbance, indicating plasma flow equatorward across the plasma sheet boundary. On the other hand, the flow profile in the $Y$ direction is related to the motion of the plasma tangential to the boundary.

To summarize the observations, each of the multiple onset seems to be associated with a north- and then southward motion of the plasma sheet boundary layer. The plasma moves first northward together with the boundary but the enhanced equatorward convection exceeds the southward boundary motion. During the plasma sheet boundary layer encounter an increase in the magnetic field gradient and an increase in the dawn-dusk flow shear are observed. This shear in the flow twists the field in a sense expected from a downward field aligned current, the predicted signature of the dawnside edge of the substorm current wedge or the night-side Region 1 type field aligned-current.

Large equatorward convection was observed also in previous substorm observation by Geotail [Taguchi et al., 1998] and by ISEE 1 and 2 [Forbes et al., 1981]. A possible interpretation of the enhanced equatorward flow and field disturbance in the lobe is a transition from closed flux reconnection in the plasma sheet to open lobe field reconnection and the associated change in the field configuration [Taguchi et al., 1998]. Based on multi-point multi-instrument observations Cluster can observe the boundary motion and plasma motion independently. During the northward tilt of the magnetic field, the plasma is also moving northward with the boundary. A possible interpretation consistent with the reconnection scenario would be that the field configuration in the lobe also changes due to closed field reconnection tailward of Cluster. When the lobe field reconnection starts, an enhancement of the convection is accompanied by a thinning of the plasma sheet, the latter speed being comparable or slower than the former. More detailed study on the ion and electron motion relative to the boundary and comparison with the reconnection scenario is planned as a future study.

4. 1838 UT onset: plasma sheet flow and current sheet thinning

Cluster was located in the plasma sheet during the 18:38 UT auroral intensification. Figure 5 shows magnetic field data from SC1-4 and $X$ component of the ion velocity from SC 1 and 3 between 18:38 and 18:48 UT. Auroral intensification was identified by IMAGE/FUV at 18:38 UT (indicated by black vertical dashed line), followed by poleward and eastward expansion around 18:44 UT and weakening around 18:47 UT (indicated by grey vertical dashed lines). The temporal scale of the auroral activation and the Cluster disturbance are quite consistent, considering
the time resolution of the IMAGE data (2 min) and the location of Cluster with regard to the onset location.

SC 3 was near the neutral sheet before the onset, whereas the other 3 satellites are in the northern plasma sheet but encountered the neutral sheet after the auroral onset. High-speed Earthward flow took place in association with an enhancement in the $B_X$ component for the three northern spacecraft (SC 1, 2, and 4) and a decrease in $B_X$ component and encounter of the southern hemisphere for SC 3. This indicates a significant steepening of the gradient in $Z$ direction due to an enhancement in the current density as well as a thinning of the plasma sheet.

![Figure 5](image1)

**Figure 5.** Magnetic field data from SC1-4 and $X$ component of the ion velocity from SC 1 and 3 between 18:38 and 18:48 UT. Auroral intensification was identified by IMAGE/FUV at 18:38 UT (indicated by a black vertical dashed line), followed by poleward and eastward expansion around 18:44 UT and weakening around 18:47 UT (indicated by grey vertical dashed lines).

It is apparent that $B_Y$ and $B_Z$ are correlated due to the flaring typical for this local time sector (tilted toward the radial direction). We therefore transformed the data into a maximum (minimum) variance coordinate system to eliminate this effect. The minimum variance analysis was performed using spin-resolution magnetic field data between 18:38 and 18:47 UT for each spacecraft independently yet obtained quite similar results. Figure 6 shows the proton velocity from SC 1, 3, and 4 and the magnetic field data from the four spacecraft in the new coordinate system. Here we define $X'$, $Y'$, $Z'$ as the maximum, intermediate, and minimum variance direction, using the result from SC 4 as a reference. The $X'$ axis is tilted toward dusk by $29^\circ$ in equatorial plane and the $Z'$ axis is tilted by $7^\circ$ toward midnight in the noon-midnight plane (in GSM coordinates). It can be seen that the high-speed flow as well as the field perturbation occurs mainly in the $X'$ direction. The flow and field disturbance can be divided into three phases, delineated by the solid lines.

![Figure 6](image2)

**Figure 6.** Magnetic field and plasma data in maximum variance coordinates (see details in text).

(1) During the first interval, when the flow started to develop, all four spacecraft first moved northward and then southward. During this interval, the field traces for each SC are quite different and so are the flow traces, which is possibly related to the spatial structure of the moving front of the high-speed plasma. During this interval, the flow at SC 3 is more developed compared to those at SC 1 or 4. Since SC 3 was located southward and closer to the central plasma sheet, the
The result shows that before the onset of the flow, the spatial scale of the current sheet is 5000 km, while during the fast flow event the scale reduces to 400 km, which is comparable to the ion gyro scale. Due to the significant deviation from the average current sheet orientation, we could not obtain any reasonable fit during the third interval. Yet, because of the large gradients between the three northern SCs (1, 2, and 4), the current structure must be even more localized, and the density more enhanced during this third interval.

(2) During the second interval, on the other hand, the three traces of the flows are more similar, although the satellites are located at quite different places relative to the neutral sheet. During this interval, therefore high-speed flow is more widespread throughout the plasma sheet.

(3) During the third flow event, the three satellites in the northern hemisphere, which are located in a plane nearly parallel to the current sheet, differed significantly in the magnetic field traces. The current sheet structure has therefore significantly changed. The flow traces, on the other hand, are not significantly different compared to the second interval.

That the magnetic field perturbation is predominantly in the $X'$ direction with a very weak $Z'$ component and that the plasma flow signature is distributed over the current sheet region makes it tempting to apply the Harris sheet model to examine the structure more quantitatively. In a Harris sheet the magnetic field is represented by $B_X(z) = B_L \tanh((z-z_0)/L)$ where $B_L$ is the lobe field, $z_0$ is the location of the neutral sheet and $L$ is a parameter related to the half-thickness of the current sheet. We can use measurements from 3 spacecraft to estimate the parameters $(z_0, B_L,$ and $L$) and can compare the estimated $B_X_{\text{model}}$ at the location of the fourth spacecraft with the actual data, $B_X_{\text{data}}$ to check the validity of the estimation. For simplification we used 30-s averaged data.

Figure 7 shows the result of the Harris sheet estimation for several sequences before and during the first two intervals of the flow when the estimates of $z_0, B_L,$ and $B_X_{\text{model}}$ obtained are reasonable, i.e., the difference between $B_X_{\text{model}}$ and $B_X_{\text{data}}$ does not exceed a factor of 2. The model results are shown as symbols using the conventional Cluster symbols (rectangle, diamond, circle, and triangle for SC 1, 2, 3, and 4) to represent that spacecraft not used for the modelling but for comparing its data with the model.

Figure 7. 30-sec averages of the magnetic field $X$ component (presented by lines) and model (symbols) of Harris current sheet half thickness and the current density.

Determination of the current sheet thickness is important to understand the possible instabilities responsible for substorms. Here we obtained a clear thinning of the plasma sheet/current sheet closely related to the high-speed flows. Such thin current sheets have been observed by the ISEE satellite pair during substorm growth phase and expansion phase [Sanny et al., 1994; Sergeev et al., 1998]. The maximum current density 30 nA/m obtained in this study is comparable to that obtained by Sergeev et al., [1998]. These authors have also identified close relationships between the thin current sheet and the fast flows. It should be noted that ion acceleration is expected to be more effective in a thin plasma sheet configuration for reconnection flows [i.e., Martin et al., 1986].
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References