Cluster observations of magnetospheric substorm behavior in the near- and mid-tail region

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Received 27 December 2002; received in revised form 3 April 2004; accepted 5 April 2004

Abstract

The Cluster constellation of spacecraft has returned substantial new data on particle and field variations in the near- and mid-magnetotail regions of Earth’s magnetosphere. Using the Research with Adaptive Particle Imaging Detectors (RAPID) system onboard the four Cluster vehicles, we have identified substorm-related energetic ($E > 20$ keV) electron enhancement events during the period March 2001 through October 2001 in the geocentric radial range of 4–19 Earth radii. We have used concurrent data from other Cluster instruments as well as from the POLAR, IMAGE, FAST, GPS, and geostationary orbit spacecraft in order to understand particle injection and transport phenomena throughout this key region of the magnetotail. Electron enhancements in the plasma sheet at intermediate radial distances have been studied in a global substorm context. A particularly well-observed substorm case occurred on August 27, 2001 when Cluster was almost exactly in the midnight meridian. We find evidence that Cluster was very near the near-Earth substorm neutral line and that magnetic reconnection began some seven minutes prior to the substorm auroral brightening of the expansive phase onset. We also study in some detail the recovery phase of the substorm and the associated expansion of the plasma sheet over the 4-satellite Cluster constellation.

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Keywords: Geomagnetic storms; Magnetospheric substorm; Near- and mid-tail regions; Cluster observations

1. Introduction

The magnetospheric research community has long sought the capability to view the Sun–Earth system in a global way and to probe concurrently the microphysical details of key physical regions. With present-day spacecraft constellations, there is an unprecedented ability to apply both telescopic and microscopic principles. It has been a further longstanding challenge in magnetospheric substorm physics to understand where and exactly when key substorm processes initiate (e.g., Baker et al., 1996). One point of view is that very near-Earth ($6–8R_E$) instabilities lead to cross-tail current disruption and auroral brightening. In this scenario, magnetic reconnection occurs subsequently and consequently in the mid-tail ($20–30R_E$) region (e.g., Lyons, 2000 and references therein). On the other hand, a case studied in detail using Geotail, geostationary Earth orbit (GEO), and ground-based data provided compelling evidence that magnetotail reconnection began prior to the near-Earth and auroral onsets of activity (Ohtani et al., 1999). Extensive statistical studies with Geotail have shown the common occurrence of magnetic reconnection signatures in the midtail region near substorm expansion phase onset (Nagai et al., 1998). What has been needed to help further clarify issues about reconnection timing...
We have examined the magnetospheric energy input for 27 August including the composite solar wind-IMF parameter, VB$_Z$, derived from ACE data (see Baker et al., 2002). The ACE data were shifted by 59 min to account for propagation time to Earth. The VB$_Z$ parameter went negative (i.e., became geoeffective) shortly after 0200 UT and stayed negative, with some fluctuations, until ~0430 UT. The auroral electrojet index AE (=AU–AL) showed a large intensification at ~0410 UT. This substorm expansion phase onset time was consistent with the dipolarization of magnetic fields seen at GOES-8 (and the subsequent “current disruption”) shown by Baker et al. (2002). An injection of $E \gtrsim 30$ KeV electrons during this substorm onset was also observed (Li et al., 2003).

3. Expansion phase onset of August 27

From auroral electrojet data, GOES data, and detailed IMAGE auroral data studied by Baker et al. (2002), we infer that a relatively long substorm growth phase occurred on 27 August extending from at least ~0230 to ~0400 UT on August 27. The electrojet index data and the GOES-8 data suggest several small onset events which we interpret as pseudobreakups (e.g., Nakamura et al., 1994). These were most prominently seen at ~0305, ~0325, and ~0345 UT. However, only the ~0410 UT onset produced a major substorm onset at GEO or on the ground.

At ~0408 UT, Wideband Imaging Camera (WIC) images from IMAGE revealed a dramatic brightening of auroral features right at local midnight and also around 20 LT (Baker et al., 2002). In the subsequent 10–15 min, the aurora exhibited a large expansion phase and breakup. By ~0430 UT, the substorm had clearly progressed toward a recovery phase. Thus, the IMAGE/WIC data support ground-based and GOES-8 data indicating that a substorm expansion phase onset occurred between 0406 and 0408 UT. Energetic neutral atom (ENA) images from IMAGE (not shown here) also support this onset timing.

Following the substorm onset timing established in earlier work, we have examined more detailed data from instruments onboard the four separate Cluster spacecraft (abbreviated C1–C4). The locations of the Cluster s/c and their relative spacing is shown in the small inset toward the bottom of Fig. 2. It is seen that C1 was closest to the Earth while C3 was slightly lower in Z$_{GSE}$ than were the other three s/c.

Fig. 2 has several main panels. Fig. 2(a) and (b) show the plasma flow moments (2a) and magnetic field components (2b) obtained from C1 for the period 0330–0500 UT. The $(X, Y, Z)$ components of flows are shown, respectively, by black, red, and green curves. The lower four panels of Fig. 2 show data from all
Fig. 2. Cluster data (as described in the text) for the period 0330–0500 UT on 27 August 2001 (from Baker et al., 2002).

four Cluster s/c according to the color coding (black, red, green, and blue) noted. In order, the data shown are: Fig. 2(c), energetic electron fluxes ($E > 30$ keV) from the RAPID experiment (Wilken et al., 1997); Fig. 2(d), plasma moments in the Earthward-tailward sense from the CIS experiment (Reme et al., 1997); Fig. 2(e), magnetic field north-south component from the FGM experiment (Balogh et al., 1997); and Fig. 2(f), electric field dawn-dusk component from the EFW experiment (Gustafsson et al., 1997). (Note that CIS velocity moments and electric field data were not available from C2.)

Fig. 2 data taken together make several points. First, during the pseudo-breakup period after $\sim 0345$ UT, there was only a brief burst of Earthward plasma flow. Otherwise, all of the Cluster spacecraft remained embedded in a rather stagnant, tenuous plasma sheet until after 0400 UT. The relatively large value of $B_x$ (Fig. 2(b)) and the small values of $B_y$ and $B_z$ show that the spacecraft were in the outer parts of a rather thick plasma sheet. Clearly the most interesting activity for the several Cluster spacecraft began at $\sim 0400$ UT. At that time, $B_x$ diminished while $B_z$ and $B_y$ both became strongly negative (see panels b and c). At $\sim 0401$ UT the plasma sensors saw strong tailward plasma flow ($V_x \sim -500$ km/s) and a small burst of energetic electrons (2c). By about 0406 UT, the magnetic field had rotated toward $B_z \sim 0$ (and more Earthward) and the plasma flow had by that time become strongly Earthward. By $\sim 0410$ UT, all Cluster spacecraft had moved into a nearly lobelike environment. This interpretation is based on the RAPID/IES electron fluxes reaching background levels (Fig. 2(c)). Even in the northern tail lobe, however, there were some field-aligned bursts of plasma ions (compare panels 2a, 2d, and 2f).

At $\sim 0422$ UT, the plasma sheet apparently expanded abruptly and re-enveloped all four of the Cluster satellites. As shown by IES data (Fig. 2(c)) the first spacecraft to be enveloped was C3, which was the one closest to the neutral sheet. C4 was the furthest from the Earth and was the last to be enveloped. The plasma flow (2a and 2d) and electric field (2f) data showed very strong Earthward flow in the recovering plasma sheet (0422–0430 UT).
Fig. 3 provides an even more detailed view of magnetic field data for the period 0355–0410 UT. Panel 3a plots the magnetic field X-component for the four Cluster spacecraft (again color-coded). Panel b shows the $B_y$-components and panel c shows the $B_z$-components. The lowest panel (d) shows the total magnetic field strength. Fig. 3(a) and (b) show interesting differences between various individual spacecraft. Overall, however, the combined, four-spacecraft data show a positive change in $B_z$ at $/C24/0401:30$ UT followed by a strong interval of southward $B_z$ (which lasted until $/C24/0406$ UT). During most of this time (see Fig. 2) there was relatively strong tailward plasma flow. At $/C24/0406$ UT the plasma flow switched to sunward (Earthward) flow and $B_y$ became more northward in orientation. Note also in Fig. 3(b) the very strong negative, or downward, perturbation of the $B_x$ component of the field from 0357 until $/C24/0409$ UT.

4. Interpretation of August 27, 2001 event

Based on the broad range of data available in this well-observed case, Baker et al. (2002) concluded that, by the usual indicators, a substorm expansion phase onset occurred at 0408 (+1 min) UT on August 27, 2001. This substorm led to a major auroral brightening and breakup, a field dipolarization at geostationary orbit, energetic particle injections (also at GEO), and ground magnetic bay signatures in a broad local time sector. In the period 0408–0410 UT there was a very evident disruption of the cross-tail current near $6.6R_E$ geocentric distance. Cluster multipoint measurements at $X = −19R_E$ gave clear evidence that magnetic reconnection commenced at $/C24/0401$ UT in the central plasma sheet at $X ∼ 18R_E$. This reconnection was of apparent broad spatial extent and it persisted for several minutes.

The sequence of events on August 27 is as shown in Fig. 4. As illustrated in Fig. 4(a), the magnetosphere went through a long growth phase during the period $/C24/0230$ to $/C24/0400$ UT. During this phase, the polar cap grew in size (as seen in available IMAGE/WIC data) and the magnetotail became more stretched and stressed (POLAR, GOES, and ground data). There were several pseudobreakups during the growth phase, but only the $/C24/0408$ UT onset led to a full substorm development. As shown in Fig. 4(b), at $/C24/0401$ UT there was onset of magnetic reconnection in the central plasma sheet at $X ∼ 18R_E$ (see Cluster data). The observed dissipation was identified as reconnection because of the negative magnetic field orientation and strong convective $(\vec{E} \times \vec{B})$ plasma flow. Over the subsequent several minutes, the plasma flow reversed direction and the magnetic field became northward. Thus, one can infer that the magnetic reconnection site (X-line) moved tailward past the Cluster constellation as shown schematically in the figure. From careful examination of the four individual Cluster spacecraft data sets, the X-line was estimated to move tailward at $100$ km/s during the time interval 0404–0406 UT (Baker et al., 2002).

It is possible that the magnetic X-line progressed from reconnection of closed (plasma sheet) to open (lobe) field
lines at \(~0408\) UT. This is indicated in Fig. 4(c). It seems that the explosive increase of reconnection rates that accompany lobe field reconnection (with the concomitant large Alfvén speeds in the inflow region of the X-line) could mark the expansion phase of the substorm (as seen in the auroral and ground-based data). This time would also mark the pinching off of the substorm plasmoid (Fig. 4(c)). However, the brightening of the poleward edge of the aurora was not particularly evident. The progression of reconnection from closed plasma sheet field lines to the eventual reconnection of open field lines is a key prediction of the near-earth neutral line (NENL) model (Baker and McPherron, 1990; Baker et al., 1996).

Finally (in agreement with the NENL model), the plasma sheet rapidly expanded during the substorm recovery phase. This is illustrated in Fig. 4(d). Both POLAR and Cluster sensors saw the plasma sheet recovery sequence quite well. Careful comparison of POLAR data and Cluster data reveals that POLAR observed the plasma sheet slightly earlier than Cluster. Thus the plasma sheet “thickening” front progressed tailward from POLAR \((-9R_E)\) to Cluster \((-19R_E)\) at high speed (Baker et al., 2002).

5. Details of magnetic field changes near the substorm X-line

Based upon the magnetic field and plasma signatures in this case, we would argue that the Cluster constellation of spacecraft got very near to the substorm reconnection neutral line during the period \(0401–0408\) UT on 27 August. This point is emphasized by the 4-s magnetic field vectors from C1 projected on the GSM \(X–Y\) plane as shown in Fig. 5. Prior to \(~0401\) UT, the magnetic field vectors were pointed sunward and were of a magnitude consistent with nearly lobelike field strength. However, as shown primarily by the middle panel of Fig. 5, during the interval \(0401–0405\) UT the magnetic field vectors were weaker (diamagnetic effect) and greatly distorted into the negative-\(Y\) direction (downward).

Fig. 6 shows the complete magnetic field configuration for all four Cluster spacecraft at a time (0357:00 UT) when the constellation was in a rather lobelike portion of the plasma sheet (i.e., the plasma sheet boundary layer). Panel a shows the equatorial \((X–Y)\) projection of field vectors. The origin of the coordinate system in each panel of Fig. 6 is at the location of Cluster 1. Cluster spacecrafts 2, 3, and 4 are shown (color coded as above) in their respective relative positions. Panel 6b shows the same type of plot...
but for a noon-midnight meridian (X–Z) projection. Finally, panel 6c shows the dawn-dusk (Y–Z) field projections.

The data in Fig. 6 emphasize the point that there were virtually no differences at 0357 UT in the vector magnetic fields seen by the four Cluster spacecraft. Thus, the gradient over spatial separations of 1000–2000 km were very weak. Note also that the magnetic fields at all four locations pointed almost entirely in the positive X direction, with only a hint of positive B. This clearly placed all spacecraft above the neutral sheet in a nearly lobelike environment, even though the Cluster constellation was 0.1–0.5\( R_E \) below the GSM Z = 0 plane.

Fig. 7 shows the Cluster magnetic field data taken at 0404:30 UT on 27 August. The format of presentation is the same as Fig. 6. Note the stark contrast in the magnetic field properties between Figs. 6 and 7. At 0404:30 UT, the magnetic field had almost no X-projection and the field was oriented strongly downward and southward. Note in Fig. 7(b) that the field was more strongly southward (more negative in Z) at the C3 location than at the other three s/c locations. This suggests that C3 was closer to the X-line. In the tetrahedron’s

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Fig. 6. Projections of magnetic field vectors in various planes at 0357:00 UT on 27 August: (a) X–Y plane; (b) X–Z planes and (c) Y–Z plane. The position of Cluster 1 is shown in the upper right quadrant. The three panels show the positions relative to C1 (black) at origin. C2 is red, C3 is green, and C4 is blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Same as Fig. 6 except for 0404:30 UT.
6. Possible neutral line configuration

We judge from the magnetic field data such as those presented in Fig. 7 that C3 probably approached closest to the neutral sheet and to the substorm X-line. We as have tried conceptually to fit the sequence of plasma flow and field orientation data to a simple X-line (as shown in Fig. 8(a)). This does not seem to describe very well the sequence of observations made by C3. Instead, a more complex neutral line structure having a magnetic “island” or compound X- and O-line configuration seems to work better.

As shown in Fig. 8(b), the Cluster spacecraft (especially C3) seemed to follow a worldline that carried the spacecraft from the northern plasma sheet boundary layer along a path that went deeper into the center of the plasma sheet. For the time 0401 UT to ~0404 UT, the plasma flow was strongly tailward. During this time, the magnetic field was mostly negative in orientation, but there was a brief “blip” of positive $B_z$ at around 0401:30 UT (see Fig. 3). This north-then-south configuration suggests a small scale plasmoid, or flux rope, configuration. Bearing in mind that there was also a very strong $B_y$ deflection at this time, a twisted flux rope (in 3-dimensions) is probably the correct picture to have in mind.

By 0406 UT, the plasma flow went from being strongly tailward (or even briefly stagnant) to being strongly Earthward-directed. By that time the magnetic field also was more northward oriented. Thus, as shown in Fig. 8(b), we conclude that C3 had moved to a position on the a Earthward side of the neutral line structure. We emphasize again, however, that the Cluster constellation in general (and C3 in particular) was hardly moving at all in inertial space. Rather, we infer that the neutral line configuration shown in Fig. 8 was probably moving tailward over the spacecraft at (we estimate) ~100 km/s. It is also possible that the plasma on the Earthward side of the reconnection site could become stagnant or at least decelerated as it encounters the magnetic field lines emanating from the Earth.

7. Recovery phase features

We see from Fig. 2 that the several Cluster spacecraft all entered a lobelike plasma and energetic particle environment after ~0410 UT. For example, the energetic electrons measured by the RAPID sensors on all four s/c were near background levels from ~0410 until ~0420 UT. In the NENL model of substorms (Baker et al., 1996), this period corresponds to a time with a very thin “residual” plasma sheet which remains in place after the substorm plasmoid has been expelled down the tail. The neutral line (in the classic NENL model) remains in the near-earth vicinity for some minutes until the substorm recovery phase begins.

During the recovery phase – as portrayed in the NENL model – the substorm X-line moves very rapidly down the magnetotail. Concurrently, the Earthward part of the plasma sheet expands rapidly and fills with hot plasma. During this phase of a substorm (as seen by spacecraft at about the Cluster location), there should be strong Earthward plasma flow, strongly northward magnetic field, and enhanced energetic particle fluxes (see, also, Nagai et al., 2002). As seen in Fig. 2 (panels d, e, and c, respectively), these features are borne out very well if we assume the recovery phase commenced at about 0420 UT.

In Fig. 9, we show a detail of the RAPID electron fluxes measured by the four Cluster spacecraft in the energy range 31–39 keV for the period 0415–0430 UT. We have smoothed the data with a running 10-point smoothing function. We see that the average electron fluxes increased by about two orders of magnitude between 0420 and 0430 UT. Thus, the recovering plasma sheet was rapidly filled with very hot electrons.

More careful examination of the individual flux profiles shows that C3 responded earliest and most strongly during the plasma sheet recovery followed by C1, then

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Fig. 8. Schematic diagram of: (a) simple X-line configuration and (b) more complex X- and O-online configuration. The “trajectory” of C3 on 27 August is sketched in panel b.
C2, and finally C4. This sequence means that the plasma sheet boundary enveloped the constellation from below and from the Earthward-to-tailward direction. Note also that all four spacecraft saw a very powerful oscillatory modulation of the fluxes with about a 90-s period. This was superimposed upon the overall buildup of fluxes that occurred on a 6–8 min timescale. This must imply that the recovering (thickening) plasma sheet either undulates or pulsates on a rather large spatial scale.

The refilling of the Plasma sheet with hot particles is quite striking both in its speed and in terms of the number of particles that must have been accelerated (heated). This is shown in Fig. 10, where we plot the energy spectra of electrons seen in the “predropout” (presubstorm) plasma sheet (i.e., prior to ∼0410 UT) and in the recovery phase period (i.e., after ∼430 UT). The spectra show that there is a huge difference in the density of 20 to ∼100 keV electrons which must have been accelerated and efficiently trapped in the expanding plasma sheet volume. As noted by Baker et al. (1996), we do not yet fully understand why or how the plasma sheet refilling occurs during the substorm recovery phase. Cluster observations of the type show here will help illuminate this issue.

8. Summary and conclusion

It should be noted that many authors have concluded (see Lyons, 2000 and references therein) that substorms initiate in the very near-Earth portion of the plasma sheet (6–8RE) and that mid-tail magnetic reconnection is a consequence, not a cause, of this near-Earth onset process. It is therefore very important to realize that for many well-observed cases such as the one presented here (see, also, Ohtani et al., 1999) magnetic reconnection and magnetotail energy dissipation begin well before near-Earth and auroral effects. These two competing pictures are shown in Fig. 11. The August 27 case favors the reconnection scenario. Moreover, the recovery phase of this substorm very much comports with the NENL model. We look forward to using our powerful telescope-microscope combination to further illuminate the undoubted relation between auroral, near-Earth, and mid-tail processes during many more substorms.
Acknowledgments

The authors thank our many ACE, Cluster, FAST, GOES, IMAGE, and SOHO colleagues for data and many useful discussions. This work was supported by grants from NASA.

References


Fig. 11. The competing pictures of substorm sequences in the magnetotail. We find strong support in the 27 August case for the “Reconnection Scenario”. 