Cluster Observations of the Postmidnight Plasma Sheet at 18 Re during Substorms

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Abstract. On August 15, 2001 the Cluster spacecraft passed through the plasma sheet at 0100 LT at a distance of 18 Re downtail. During the passage, three substorms were observed. Each substorm was characterized by an increase in Bz or dipolarization. The first and last substorms were also accompanied by strong earthward flows. We utilize a variety of ground and spacecraft observations to establish the circumstances of these correlated changes. For the entire interval, the IMF By was strongly positive. For the first two substorms, the IMF Bz was significantly negative prior to the onset, but the third substorm occurred during very weak southward field. The Cluster field data indicate that IMF By significantly affected the magnetic field at 18 Re causing it to pass through the current sheet at an angle to the Z-axis. A principal axis system that best organizes the magnetic field is rotated in the opposite direction expected for IMF By effects in the tail. In two substorms, the arrival of flows at Cluster was associated with an intensification of an ongoing substorm expansion. The first substorm provides a clear example of a steep front of thickening of the plasma sheet passing over the spacecraft followed by several oscillations in vertical thickness. The third substorm took place as the spacecraft were approaching the expected position of the neutral sheet. It began with a very sharp negative perturbation in Bz followed by a brief burst of tailward flow. The usual signatures of dipolarization followed. This dipolarization occurs in a step-wise manner with each field increment accompanied by a burst of earthward flow. We utilize the magnetic field and plasma flow to calculate the rate of transport of magnetic flux past each spacecraft. With the help of radar measurements of the polar cap potential from the SuperDARN network we show that a channel of width 7.8 Re can account for all of the magnetic flux entering the magnetotail during the interval of plasma flow.
1. Introduction
Thirty-eight years have passed since the concept of a substorm was introduced [Akasofu, 1964]. Despite intensive study and a voluminous literature the cause of the expansion phase onset remains a subject of intense controversy [Baker et al., 1996]. The standard substorm paradigm, the near-Earth neutral line model, explains the expansion phase as the consequence of reconnection at a localized x-line behind the Earth. In this model, reconnection of closed field lines begins in the plasma sheet shortly before the onset of auroral brightening. Rapid Earthward flows transport the reconnected field lines toward the Earth where some of the returned flux dipolarizes the field and the remainder is diverted around the Earth to return to the dayside. The arrival of the first flow in the inner magnetosphere is assumed to cause the auroral onset. Usually within minutes after auroral onset, reconnection reaches open field lines of the lobe and begins to convert them to closed field lines in the plasma sheet.

Earthward flows in the plasma sheet have been observed from the beginning of measurements in the tail [Hones et al., 1972]. The significance of these flows has also been a subject of controversy [Lui et al., 1978], with some authors arguing that the flows were field-aligned and hence not transporting magnetic flux [Rostoker, 1987]. It is now well established that both types of flow coexist, field-aligned at the boundary, and convective in the center of the plasma sheet [Angelopoulos et al., 1992a; Angelopoulos et al., 1992b; Baumjohann et al., 1990].

There is still a question of how effective the flows are in transporting magnetic flux since the flows are transient and localized [Angelopoulos et al., 1997; Angelopoulos et al., 1992a; Angelopoulos et al., 1996; Angelopoulos et al., 1992b; Angelopoulos et al., 1994]. Current best estimates of the width of the flow channels are ~ 7 Re or less [Angelopoulos et al., 1997]. They are not seen in all substorms leading some researchers to conclude that the flows are not a fundamental signature of substorm onset. However, it is obvious that if the flows are localized a single spacecraft will not observe them in every substorm. To estimate the probability of detection and whether it is consistent with observations, it is necessary to know the width of typical flow channels.

The primary purpose of this paper is to estimate the width of a convective flow channel during substorm activity. To do this we utilize magnetometers and plasma detectors on the four Cluster spacecraft as they pass through the tail current sheet. Also contributing to the estimate are observations of the upstream solar wind by ACE and the IMF by Geotail, and the polar cap potential by the SuperDARN radar network.

2. Event Overview
On August 15, 2001 Cluster passed through the tail current at a distance of ~18 Re and local time about 0120. The transit lasted for the first 12 hours of the day during which time three substorms occurred. The preliminary auroral electrojet indices for this day (not shown) suggest substorm activity was quite weak reaching only about 300 nT in the strongest substorm.

Geomagnetic activity on this day was driven by the weak interplanetary magnetic field plotted in Figure 1. Geotail was located immediately upstream of the bow shock so the delay in arrival of the IMF at the magnetopause is less than five minutes. The field magnitude was only 4 nT, most

![Figure 1: The interplanetary magnetic field measured by Geotail immediately upstream of the bow shock almost on the Earth-Sun line. Note the persistent, strong By component and a Bz component that is quite weak during the third substorm. Vertical lines show times of Pi 2 bursts.](image-url)
of which was in the By component. Bz was weak and fluctuating during the first substorm, moderate and steady in the second, and nearly zero in the third. Pi 2 onsets determined from ground observations shown by vertical lines are not obviously correlated with northward turnings of the IMF.

The solar wind plasma moments measured by ACE at the L1 point were quite steady. The density was rather low (2 cm$^{-3}$) and the velocity was steady (450 km/s) creating a dynamic pressure of only 0.8 nP. There was a slight change in direction of the solar wind after 0430 UT due to a change in Vy.

The magnetic field observations made by the fluxgate magnetometer on the Cluster spacecraft [Balogh et al., 1997] are plotted in Figure 2. $B_{lobe}$ calculated from the total pressure suggests that the spacecraft was in the north lobe at 0115 and probably entered the southern lobe about 1330 UT. The neutral sheet crossing occurred between 0800-0900 UT as evident from the zero crossing of Bx. The By component was quite strong and changed sign, but not at the same time as Bx. We show in the next section that these two facts imply both that the field lies more in a meridian plane through the spacecraft than in the noon-midnight meridian plane, and that the tail field has been distorted by the By component of the IMF. Large increases in the Z component of the magnetic field are associated with each substorm. On average, these increases are preceded by a swarm of Pi 2 onsets. Major onsets are followed by the largest changes in Bz. It should be noted that the main dipolarization at Cluster in the second substorm was significantly delayed relative to ground activity. Below we use the third substorm to demonstrate that its increase in Bz was associated with earthward transport of magnetic flux by convective flow bursts.

The three GSM components of the ion flow velocity as measured by the CIS instrument on Cluster #1 are plotted in Figure 3. Two intervals of high-speed earthward flow (Vx) are associated with the first and last substorm. The flows are strongly earthward.

Figure 2. The three GSM components of the magnetic field measured by Cluster in the morning sector. The X component shows the passage through the current sheet. The Z component indicates three intervals of dipolarization associated with the three substorms. Vertical lines are labeled with the start time of Pi 2 bursts. Solid vertical lines indicate major onsets.

CLUSTER #1 ION FLOW VELOCITY IN GSM COORDINATES

Figure 3. The GSM components of the ion flow measured by the CIS instrument on Cluster #1. Two intervals of earthward flow are associated with the first and last substorm. The flows are strongly earthward.

The three GSM components of the ion flow velocity as measured by the CIS instrumentation [Rème et al., 1997; Rème et al., 2001] are plotted in Figure 3. Two intervals of high-speed earthward flow (Vx) are associated with the first and last substorm. These were accompanied by significant variations in other components as well. However, the second and largest, substorm on the ground was not seen in the plasma flow although it was clearly seen in the magnetic field.

3. Minimum Variance Analysis

To simplify the study of the magnetic field data, we have rotated it to a principal axis coordinate system based on the entire current sheet crossing. We do this by finding the eigen values and eigen vectors of the variance matrix. This matrix is
defined as the (3 by 3) matrix with elements $V_{ij}$
given by

$$V = \frac{1}{N} \sum_{i=1}^{N} \left( B_i(\alpha) - \langle B_i \rangle \right) \left( B_j(\alpha) - \langle B_j \rangle \right)$$

where $B_i$ and $B_j$ are two Cartesian components of the field, $N$ is the total number of points in the
time interval considered, and $\langle \rangle$ denote the average of the time series over the $N$ points. The
resulting matrix is modified by reflections to make the new axes correspond as closely as
possible to the GSM axes. The diagonal elements of the original matrix in GSM coordinates are
240.9, 17.5, and 6.7.

The result of eigen analysis for the interval 00-15
UT on August 15, 2001 is the rotation matrix

$$Rot = \begin{pmatrix}
0.9671 & 0.2446 & -0.0693 \\
-0.2254 & 0.9514 & -0.2098 \\
-0.1177 & 0.1872 & 0.9752
\end{pmatrix}$$

having the eigenvalues 257.3, 2.16, and 5.6. The
eigenvalues should be compared to the original
diagonal elements given above. Note in the final
principal axis (PAX) system, the largest variation
is in X and the smallest is in Y. Each row of the
matrix $Rot$ is a PAX unit vector expressed in
GSM coordinates. This matrix is very nearly equal
to the product of two rotations as described next.

Instead of minimizing the full 3 by 3 variance
matrix in a single step, first diagonalize the 2 by 2
submatrix corresponding to the GSM X-Y plane.
This transformation is a rotation of 14.2 degrees
about the GSM -Z axis so that the magnetic field
lies primarily in the new X-Z plane. This rotation
eliminates the zero crossing in By that is a
consequence of the meridional orientation of the
magnetic field inside the plasma sheet. In the
rotated system the new Y component does not
change sign and has a mean value of +2.0 nT with
a rms deviation of 1.5 nT. We attribute this
average to reconnection of the Earth’s field to the
IMF which for this crossing averaged about +4
nT.

In the second step, we calculate the 3 x 3 variance
matrix in the system rotated by the first transformation. We then diagonalize the 2 x 2
submatrix corresponding to the Y-Z plane. This
transformation is a rotation of −8.99 degrees about
the X-axis. This rotates the new Y-axis axis so it
is lower on the dusk side and higher on the dawn
side than the GSM unit vectors. If this rotation
were a real rotation of the plasma sheet, we would
expect the satellite to be closer to the neutral sheet
than predicted by statistical formulas for the
position of the neutral sheet [Fairfield, 1980]. As
discussed later this rotation about X is opposite to
that expected from the known By effect on the
neutral sheet [Kaymaz et al., 1994].

4. Substorm Timing

Substorm onsets were timed by examination of a
combination of auroral zone magnetograms and Pi
2 pulsation data. For the third substorm, keograms
were also available from CANOPUS scanning
photometers, however, only the Fort Smith sky
was unclouded. The keogram for the third
substorm indicates that the expansion began to the
south of Fort Smith (at elev. angle < 60°) just
before 0730 UT. The expansion was preceded by
two weak intensifications at 0726 and 0728.
Subsequent to the onset there were major
intensifications of the expansion at 0742 and 0757
UT.

The Pi 2 data for this event were obtained by
filtering fluxgate magnetometer data into the Pi
2 band and calculating the instantaneous horizontal
amplitude for each station. Several onsets were
found in each substorm. We selected those onsets
that were associated with poleward motion of the
electrojet or the aurora as major onsets. Minor Pi
2 onsets are denoted in the figures by vertical
dashed lines and major onsets by solid lines.

5. Flux Transport

During the third substorm there was a prolonged
interval of earthward flow associated with a
gradual increase in Bz. Figure 4 shows the data
for this event. The top panel indicates that Bz
more than doubled at all four spacecraft from
about 2 to >5 nT. Reference to Figure 2 shows
that Bz actually reached a maximum of ~7 nT
about 0900. At the same time convective flows
were observed at all spacecraft. The component of
the flow perpendicular to B at three of the
spacecraft (#1 black, #3 green, #4 blue) is plotted
in the middle panel. The flows were bursty with
peak earthward velocity reaching 900 km/s. The Y-component of the electric field at each spacecraft calculated from \(-V \times B\) is plotted in the bottom panel. The flows produced spikes in the electric field as high as 8 mV/m. A close study reveals that the earthward component of the flow was slightly different at each spacecraft with #3 strongest, #1 intermediate, and #4 weakest. No plasma data are available from #2.

The difference in flow velocity between spacecraft is most likely a result of their vertical separation. In an equatorial projection spacecraft #1, #3, and #4 were very close together (<500 km). However, in the noon-midnight meridian plane their separation was larger with #3 closest to the neutral sheet, #1 at intermediate distance, and #4 the highest. This is the same ordering as the flow velocities, and as we show next, of the total amount of magnetic flux passing each spacecraft.

If we assume that we have a flow channel with uniform velocity and vertical magnetic field then the rate of transport of magnetic flux across an east-west line through the spacecraft is

\[
\frac{d\Phi_M}{dt} = D_N \left( V_x B_n \right) = D_N E_y = \Theta_{ps},
\]

where \(\Phi_M\) is the magnetic flux, \(D_N\) is the width of the flow channel, \(V_x\) is the earthward plasma flow velocity, \(B_n\) is the magnetic field normal to the flow, \(E_y\) is the electric field caused by the flow, and \(\Theta_{ps}\) is the total potential drop across the channel. Thus, the total flux transported in this interval of time is given by the product of the width of the flow channel and the integral of the instantaneous electric field.

\[
\int_0^t V_x B_n dt = D_N \int_0^t E_y dt = \int_0^t \Theta_{ps}(t) dt
\]

where we assume that the width of the channel is constant. In addition, we note that the lobe field was nearly unchanged during the 45-minute interval. This implies that day and nightside reconnection rates were nearly balanced. In this case, magnetic flux enters the lobe at the same rate it leaves it so that the electric fields in the lobe and the plasma sheet are the same. However, the lobe electric field maps into the polar cap creating the polar cap potential. Thus, we can replace the plasma sheet potential by the observed polar cap potential. Replacing the integrals by sums and solving for \(L_N\) we obtain

\[
\left( \frac{D_N}{R_e} \right) = \left( \frac{\Delta t_{sd}}{\Delta t_{cl}} \right) \sum_j \frac{\Theta_{PC}(i)}{\sum_j R_j V_j B_n(j)}
\]

where \(\Delta t_{sd}\) and \(\Delta t_{cl}\) are respectively the sample rates of the SuperDARN polar cap potential and Cluster time series. We have done this integral for the three spacecraft having plasma measurements obtaining the results presented in Figure 5.

For a channel of width 1-Re, a total of 17, 20, or...
25 MWb/Re passed the various spacecraft in the interval 0745-0845. During this substorm the SuperDARN radar network made excellent measurements of the polar cap potential showing it was a steady 50 kV. Substituting the observed flux transport for spacecraft #1 we obtain a channel width $D_N = 7.8$ Re. A possible explanation for the differences in flux transport at the three spacecraft is discussed in the next section.

6. Discussion

We have presented data from a Cluster pass through the tail current on August 15, 2001. The pass occurred in the morning sector at about 0120 local time and a radial distance of approximately 18 Re. During the passage, three weak substorms were observed in the auroral zone. We have used ground magnetometer and Pi 2 pulsation data to time onsets during these substorms. Each substorm caused a clear dipolarization of the local field evident as an increase in Bz in the plasma sheet. In contrast to the more usual situation, the lobe field did not vary in a systematic way with substorm phase suggesting that the input of flux to the lobe from the solar wind was balanced by flux removed by the substorm expansions. The first and third substorms were accompanied by strong, convective earthward flows.

Substorm activity during this passage was driven by a steady solar wind with low dynamic pressure, and a weak magnetic field oriented towards dusk. Dayside reconnection appears to have been dominated by the By component of the IMF. We found evidence that 50% (~2 nT) of the IMF By penetrated the tail lobes and plasma sheet.

The results of the minimum variance analysis did not correspond to expectations based on the IMF-By. The full transformation is well approximated by the product of two rotations. The first rotation of 14° about the GSM-Z axis aligns the new X-axis with the meridian containing the magnetic field through Cluster. This rotation eliminates the change in sign of By and leaves a constant 2 nT By through the plasma sheet. The second rotation is -9° about the new X-axis dropping the final Y-axis below the GSM equatorial plane. This rotation does not significantly affect the mean value of By, and only decreases the Y-variance by about 5%. However, this rotation is opposite to that expected for the By effect on the neutral sheet as discussed in following paragraphs.

Although it may be coincidental, it is interesting to note that the second rotation is just that required to eliminate the steady Y-component of the field at the peak of the substorm dipolarization events. At the end of each substorm expansion, Bz in the principal axis system is approximately 13 nT. The angle defined by arctan(2/13) is 8.7°. Why this should be the case is not clear since the second rotation is determined by the variance in the Y and Z components of the field, and not the steady field. Possibly the polarization of substorm associated waves in the plasma sheet is determined by the topology of the background field.

Previous studies have shown that a fraction of the IMF By is present in the tail creating a By in the lobes and plasma sheet that has the same direction as in the IMF. Cowley [1981] demonstrated that a positive IMF By preferentially enters the northern lobe on the dawn flank and exits from the southern lobe on the dusk flank producing a By component in the lobes with the same sign as the IMF. Moses et al. [1985] studied the effects of the IMF on field lines that close through the plasma sheet. They argued that the tension from newly opened field lines displaces ionospheric convection in a polar cap towards the same flank that the IMF enters the lobe connected to this polar cap. Then, when the field lines reconnect in the tail, the meridian of the newly closed field lines is tilted in the same direction as the IMF By. An alternate explanation was suggested by Khurana et al. [1996]. They noted that the preferential entry of open flux into a particular quadrant of the lobe would produce a magnetic pressure gradient that stimulates a flow toward the adjacent quadrant. This flow persists after the field lines reconnect resulting in a vertical shear of flow inside the plasma sheet. This shear tilts the plasma sheet magnetic field so that it has the same By component as the IMF and lobe fields.

A detailed statistical study of four years of IMP-8 observations in the tail by Kaymaz et al. [1994] confirms that the IMF By penetrates both the lobe
and plasma sheet. In addition, the study shows that the IMF By rotates the neutral sheet about the X-axis in the direction expected if the exit field applies a torque to the tail. For a positive By the field exits on the dusk flank of the south lobe. Thus, viewed from the Sun the neutral sheet appears to be lifted up on the dusk side.

We find that the response of the tail field and plasma flows at this dawn location and distance of Cluster is not closely correlated in time with substorm onsets measured on the ground. In general, it appears that Cluster responds late in the expansion phase following an expansion of the auroral bulge to higher latitudes. Most of the dipolarization at Cluster follows the last Pi 2 onset seen on the ground. This may reflect the delayed arrival of substorm expansion at post-midnight LT locations due to a widening of the auroral bulge.

During the third substorm we have unusually good coverage of the ground with auroral keograms, magnetometers, and the SuperDARN radar network. This substorm was particularly interesting because of a prolonged interval of earthward transport of magnetic flux by a sequence of bursty flows. Since both the IMF and the lobe field remained almost constant during this interval, we assume that flux input and output from the lobe were balanced. The plasma flow velocity and magnetic field were used to calculate the Y-component of the electric field, which was interpreted as the rate of transport of magnetic flux per unit length. By equating the time integral of the observed polar cap potential to the calculated potential in the plasma sheet, we obtained an estimate of the width of the flow channel necessary to maintain a constant lobe field. If all of the polar cap potential is associated with the returning flux, we obtain a channel width of 7.8 Re. We also noted that the calculated total flux passing a spacecraft decreased with its height. Since higher spacecraft map farther down the tail this implies less flux passes a line further down the tail. This behavior could be caused by a narrowing of the flow channel as it approaches the Earth. Narrowing would cause the electric field across the channel to increase towards the earth. The assumption of a constant channel width then leads to apparently more flux. The same effect could be produced by entrainment of flux through the sides of a channel of constant width.

Our result should be compared to the statistical results of Angelopoulos et al. [1994]. In their study of bursty bulk flows (BBFs), the authors found that the average duration of a BBF was 550 s and that each BBF transported total magnetic flux averaging $2.5 \times 10^8$ MWb/Re. Assuming arbitrarily that a flow channel is 3 Re wide they concluded that a single BBF transported only about 2% of the total flux necessary to create a substorm driven by a polar cap potential of 150 kV. In contrast, we conclude that 100% of the flux entering the lobe during this interval of time could have been returned by the observed flow. Note, however, that for an event in which data were available from two spacecraft in the tail Angelopoulos et al. [1997] concluded that a channel ~7 Re wide could account for the necessary flux transport in a sequence of bursty flows.

What accounts for the discrepancy of a factor of 50 between our result and that in Angelopoulos et al. [1994]? First it should be noted that our flux transfer event had a duration 5.6 times longer than their average BBF. In addition, the total flux transported per Re in our event was eight times larger than in their average events, and our polar cap potential was a factor of 2-3 smaller than they assumed was typical for substorms. Finally, we used a channel 2.6 times wider than their channel width. The product of these factors, $8 \times 2.6 \times (2-3) = 42-62$, nicely brackets the difference.

Our results for the third substorm should be contrasted to those for the second substorm. In the second substorm, Cluster observed a weaker dipolarization than it did in either of the other two. In addition, there was essentially no plasma flow observed during this substorm. How then does the magnetic flux increase locally? The best guess is that during this event Cluster was located adjacent to a flow channel and that the flux appearing at the spacecraft is transported to the spacecraft by weak and possibly turbulent flows that are not obvious in the measurements. This result is also consistent with previous observations by Angelopoulos et al. [1997] who found strong flow at one spacecraft and no flow less than 3 Re away.
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