Cluster observations of quasi-periodic impulsive signatures in the dayside northern lobe: High-latitude flux transfer events?

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We report on a series of quasi-periodic reversals in GSM $B_Z$ observed by the four Cluster spacecraft in the northern dayside lobe poleward of the cusp on 23 February 2001. During an interval of about 35 min, multiple reversals (negative to positive) in $B_Z$ of approximately 1-min duration with an approximate 8-min recurrence time were observed. The individual structures do not resemble low-latitude flux transfer events (FTE) [Russell and Elphic, 1979] but the 8-min recurrence frequency suggests that intermittent reconnection may be occurring. Measurements (appropriately lagged) of the solar wind at ACE show that the IMF was southward-oriented with a strong $B_X$ and that a modest dynamic pressure increase occurred as the events started. The multi-point observations afforded by the Cluster spacecraft were used to infer the motion (direction and speed) of the observed magnetic field reversals. The associated currents were also calculated and they are consistent with the spatial confinement of the observed magnetic field reversals. We propose that the observed reversals are due to flux tubes reconnecting with closed field lines on the dayside. Ancillary data from the Cluster Ion Spectrometry (CIS) and Plasma Electron And Current Experiment (PEACE) instruments were used to develop a physical picture of the reversals.

INDEX TERMS: 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2728 Magnetospheric Physics: Magnetosheath; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2731 Magnetospheric Physics: Magnetosphere—outer; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; KEYWORDS: magnetopause, flux transfer event, reconnection, Cluster


1. Introduction

[2] A primary mechanism by which solar wind mass, energy, and momentum are transferred into the magnetosphere is reconnection [Dungey, 1961; Russell and McPherron, 1973; Gonzalez, 1990]. The process is thought to occur in quasi-steady state [Paschmann et al., 1979; Newell and Meng, 1995] and also intermittently [Russell and Elphic, 1978, 1979; Lockwood and Smith, 1989]. The relative occurrence of each type of reconnection is actively debated. Time-varying reconnection is thought to produce flux transfer events (FTE) [Russell and Elphic, 1978, 1979]. FTEs are characterized in low-latitude observations by a bipolar variation of the magnetic field component normal to the magnetopause (in local boundary normal coordinates) and an increase in the field magnitude. At the low-latitude magnetopause FTEs recur typically at 8-min intervals [Rijnbeek et al., 1984; Lockwood and Wild, 1993; Kuo et al., 1995]. This quasi-periodicity has been supported elsewhere by ionospheric observations of auroral transients [e.g., Fasel et al., 1994].

[3] Several models have been developed to explain the observed magnetic field signatures at the equatorial magnetopause (see Scholer [1995] and Lockwood and Hapgood [1998] for an extended review). Russell and Elphic [1979] proposed a model in which a magnetosheath flux tube reconnects across the magnetopause and causes adjacent flux tubes to drape and flow around it as it advances to higher latitudes along the magnetopause. The draping produces the familiar bipolar $B_Z$ signature. Scholer [1988] and Southwood et al. [1998] modeled the FTE as the consequence of a temporary increase in reconnection rate that produces a “bubble” of field and plasma that then propagates along the magnetopause, the bubble producing a

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bipolar $B_N$. This model better explains certain ionospheric signatures of FTEs such as discontinuous steps in cusp velocity dispersed ion signatures (VDIS) [Lockwood et al., 1993]. Lee and Fu [1985] proposed a model invoking multiple x-lines due to tearing mode reconnection. This results in structures that have a flux rope field topology. Sibeck et al. [1989] suggested that FTE signatures are produced by dynamic pressure pulses that cause localized indentations of the magnetopause (and the associated bipolar $B_N$), thus eliminating the need for reconnection. Each of these models can readily explain the typical signatures of FTEs at low latitudes. It is unclear how FTEs evolve as they advance along the magnetopause to high latitudes, into the polar cusp, and thence into the dayside lobes. Owen et al. [2001] detail apparent high-latitude FTEs using Cluster magnetometer and electron data from February 2001. The FTEs occur 3 weeks prior to the events discussed here, so Cluster was in a similar orbit. The magnetometer signatures of the FTEs are similar to those observed at low latitudes. Furthermore, Wild et al. [2001] provide observations of apparent FTEs only about a week prior to the events discussed here. These FTEs also show the magnetic signature of low latitude FTEs and are linked to ionospheric signatures. We will see that the events described in this paper do not adhere to the magnetic signature of low latitude FTEs.

[4] The strong dependence of magnetopause reconnection on the sign of the interplanetary magnetic field $z$-component has been established through countless studies; at low latitudes, FTEs occur when the IMF $B_Z$ is negative [Berchem and Russell, 1984]. The effects of the $B_Y$ component on reconnection (e.g., cusp location, twisting of the magneto-tail) have also been explored [e.g., Crooker, 1979; Sibeck et al., 1985]. Less well understood is the role of the $B_X$ component of the IMF, especially for intervals when $B_X$ is the dominant component of the IMF.

[5] In this paper we present data for an event observed in the northern lobe with features suggestive of intermittent reconnection but of a form quite different from that observed equatorward of the cusp. On 23 February 2001, 2030-2130 UT, the Cluster spacecraft were located in the northern dayside lobe at $\sim (3.5, -1, 9.2) \text{ R}_E \text{ GSM}$. The spacecraft tetrahedron was nearly ideal with typical separations of $\sim 500 \text{ km}$, a configuration well suited for studying small-scale magnetospheric structure. The magnetic field observed at Cluster was strongly southward oriented ($5, -8, -50) \text{ nT GSM}$. The magnetometer recorded quasi-periodic reversals of the local $B_Z$ component lasting 1–2 min with a recurrence period of $\sim 8$ min. During the interval of multiple reversals the IMF $B_Z$ was negative and $B_X$ and $B_Y$ were the dominant components of the IMF. The periodic field rotations at a time of southward IMF suggest that Cluster observed FTEs arising from time-dependent reconnection although the bipolar transverse ($B_N$) perturbations that characterize low-latitude FTEs were not observed. Our analysis of these observations and the evidence that reconnection must be involved is presented in the remainder of this paper.

2. Instrumentation

[6] The Cluster mission consists of four spacecraft with identical instrument complements that were launched in 2000 into eccentric polar orbits with nominal apogee 19.6 R$_E$ and perigee 4 R$_E$. The spacecraft have a 4 s spin period and the spin axes are approximately perpendicular to the ecliptic plane. In orbit the spacecraft tetrad maintains an approximately tetrahedral shape with interspacecraft distances varying from a few hundred kilometers to a few R$_E$. Because the Cluster orbit is nearly fixed in inertial space, measurements of the magnetosphere are acquired at all local times in the span of a year.

[7] This study is based on measurements from several Cluster investigations. The Cluster magnetometer instrument (FGM) [Balogh et al., 2001] consists of two triaxial fluxgate magnetometers with sample rates up to 67 vectors per second and resolution up to 8 pT. The magnetometer has four range resolutions, ±64 nT, ±256 nT, ±1024 nT, and ±4096 nT. For the purposes of this study, high-resolution (22 vectors per second) and spin-averaged (4-s) magnetic field data have been used.

[8] The Cluster Ion Spectrometry experiment (CIS) [Rème et al., 2001] consists of two instruments for measuring ions. CODIF (Composition and Distribution Function) measures H$^+$, He$^+$, He$^{++}$, and O$^+$ from 0 to 40 keV/e with mass discrimination and 22.5º angular resolution. HIA (Hot Ion Analyzer) does not have mass discrimination but has a higher angular resolution than CODIF (5.6º). HIA measures ions from 5 eV/e to 32 keV/e. CODIF data are used in this study.

[9] The Plasma Electron And Current Experiment (PEACE) (A. Fazakerley et al., manuscript in preparation, 2004) consists of two electrostatic analyzers that measure electrons from 0.6 eV to 26.4 keV. The instrument measures complete three-dimensional velocity distributions every 4 s and every 2 s in the energy range covered by both sensors. However, only pitch angle data are transmitted in normal spacecraft telemetry mode, and full three-dimensional distributions are usually only sent in intervals of burst mode spacecraft telemetry.

[10] We also use solar wind data from the Advanced Composition Explorer (ACE) spacecraft [Stone et al., 1998] which provides continuous solar wind monitoring around the L1 Lagrange point about 235 R$_E$ upstream of the magnetosphere. The MAG (Magnetic Fields Experiment) [Smith et al., 1998] instrument provides the three components of the IMF in GSM coordinates at up to 6 vectors per second resolution. We have used 16-s MAG averages for this study. SWEPAM (Solar Wind Electron Proton Alpha Monitor [McComas et al., 1998]) provides measurements of proton velocity and number density at 64-s resolution.

3. Data

3.1. Cluster FGM Observations

[11] Figure 1 displays a whisker plot of the magnetometer measurements from the Cluster 1 spacecraft on 22 and 23 February 2001 in the Z$_{GSM}$-X$_{GSM}$ plane. The plane of the Cluster orbit at this time was within 10º of the noon-midnight meridian. The Cluster spacecraft were inbound from the solar wind on 22 February, progressed across the southern polar cap onto the nightside, and then into the northern dayside lobe on 23 February. In the GSM coordinate system, the spacecraft were slightly on the dayside at this time (Y$_{GSM}$ ~ −1). The data are 4-s spin-averages and a whisker is plotted every 50 points (200 seconds). Reversals
of the $B_Z$ component occurred between 2030 UT and 2130 UT on 23 February. During this interval the whiskers are plotted at 4 s resolution in Figure 1 and the reversals in $B_Z$ are evident. The plotted field lines are from the Tsyganenko 1996 geomagnetic field model. The field lines are plotted at 2-hour intervals and are traced from the GSM position of Cluster at the times indicated along the trajectory using appropriately lagged solar wind inputs to the model. The model field lines suggest that Cluster is inside the magnetosphere when the $B_Z$ reversals are observed at 2035 UT. The model field lines at 2200 and 2400 UT give an idea of the model magnetopause location.

Figure 1. Whisker plot of Cluster 1 magnetometer data along the Cluster 1 trajectory in the $Z_{GSM}$-$X_{GSM}$ plane from 22–23 February 2001. The orbit is inbound through the Southern Hemisphere and outbound through the Northern Hemisphere. The whiskers are plotted every 50 points (200 s) except during the interval of interest (2000–2100 UT) where the whiskers are plotted every 4 s. The plotted field lines are from a dynamic Tsyganenko 1996 geomagnetic field model selected to correspond to changing input conditions over the period of Cluster’s orbit. See text for further details.

Figure 2 shows the 4-s spin-averaged GSM $B_X$, $B_Y$, $B_Z$, and total magnetic field measurements from Cluster 1 between 1845 UT and 2200 UT on 23 February. The background field is oriented almost in the negative $B_Z$ direction. This indicates that the Cluster spacecraft are located in the northern dayside lobe northward of the cusp. The background $B_X$ is positive, as expected in the high latitude northern dayside lobe. The background $B_Y$ is negative, which requires some discussion because Cluster is located slightly on the dawn side where flaring alone would result in a positive $B_Y$. Included in Figure 2 are the predicted magnetic field component values along the orbital trajectory of Cluster 1 from the Tsyganenko 1996 geomagnetic field model [Tsyganenko, 1995]. The T96 model is parameterized by Dst, IMF $B_X$, IMF $B_Z$, and dynamic pressure. The model predicts the Cluster observations remarkably well except for the positive $B_Y$ component. Solar wind $B_Y$, $B_Z$, and dynamic pressure from the ACE spacecraft (shown in Figure 3) were used as inputs to the model. It has often been noted that the $B_Y$ component of the IMF partially penetrates the magnetosphere [Cowley and Hughes, 1983; Wing et al., 1995], a feature that may not be accurately represented in the field model. The magnetotail may have been twisted such that the symmetry of the magnetosphere was about a surface rotated counterclockwise about $X_{GSM}$ so that Cluster was effectively in the duskside magnetosphere despite the GSM location of the spacecraft on the dawn side. This would account for the negative $B_Y$ signature observed at Cluster. However, the disagreement in the $B_Y$ component may result from uncertainty in propagating the solar wind magnetic field from ~235 RE upstream to the magnetopause. Uncertainty in timing could change the sign of IMF $B_Y$ without changing either $B_X$ or $B_Z$ (see Figure 3).

The four primary reversals in $B_Z$ are shown in Figure 2c. These reversals show rapid change from negative $B_Z$ to positive $B_Z$, accompanied by a decrease in the total field magnitude at each zero crossing. Each reversal lasts for ~1–2 min and ~8 min elapse between reversals. The rotation from negative to positive $B_Z$ is abrupt (~6 s) but the rotation back to negative $B_Z$ is more prolonged, taking ~1 minute. The total $\Delta B_Z \sim 80$ nT. The $B_X$ component is slightly positive (~5–10 nT) during the interval but becomes negative during each of
the reversals, with $\Delta B_X \sim -40$ nT during reversal a. The B$_Y$ component is negative ($\sim -15$ nT) during most of the interval but $\Delta B_Y \sim -40$ nT for reversals a and b and $\sim 25$ nT for reversal c. Reversal d first shows a negative B$_Y$ followed by a strong positive B$_Y$ in excess of 50 nT before becoming negative again. Figure 4 displays the 0.045-second resolution B$_X$, B$_Y$, B$_Z$, and B from all four Cluster spacecraft for the four B$_Z$ reversals. Note the decrease of the field magnitude to less than 10 nT at the first zero crossing of the B$_Z$ component for reversal a just after 2035:15 UT. The decrease is most rapid at Cluster 3 and progressively widens as each successive spacecraft encounters the reversal. Reversals b, c, and d show more variability than reversal a and Cluster 3 misses reversal c. This indicates that the structure Cluster encountered is quite small ($\sim 1000$ km) or that the spacecraft are straddling the boundary of a larger structure.

### 3.1.1. Additional Periodic Rotations

The magnetometer data presented in Figure 2 suggest that structures similar to those producing the clear reversals in B$_Z$ are present both before and after the main reversals a, b, c, and d. Examples of these structures can be seen at 2014:49 UT, 2017:34 UT, 2023:16 UT, 2028:40 UT, 2107:40 UT, 2115:08 UT, and 2118:50 UT, indicated by dashed vertical lines in Figure 2. The first four structures appear as increases in B$_Z$ (i.e., less negative), while the final three structures show reversals in B$_Z$ but the signatures are less organized than the four main reversals. The spatial scale of the main reversals ($\sim 1000$ km) may indicate that similar structures are nearby but Cluster does not pass directly through them. Rather, Cluster may pass through the wakes of these structures. As a result, hints of these structures appear in the magnetometer data, especially for the events prior to the main reversals.

### 3.2. Cluster CIS Observations

Figure 5a displays the H$^+$ number density from the Cluster-4 CIS/CODIF instrument between 1930 and 2200 UT. The four labeled solid vertical lines indicate the approximate times of the B$_Z$ reversals, which are shown in the Cluster-4 B$_Z$ trace in Figure 5g. The additional periodic reversals indicated by the vertical dashed lines also link to particle signatures in CIS/CODIF. In particular, the first fluctuation...
observed at 2014:49 UT is associated with a pronounced decrease in \( V_Z \) and smaller increases in \( V_X \) and \( V_Y \). The proton differential energy flux spectrogram (not shown) for this interval indicates a gradual increase in proton energy expected for a passage through the mantle moving towards the magnetopause [Rosenbauer et al., 1975; Haerendel et al., 1978]. There is no clear crossing of the magnetopause. However, the densities (\( \approx 20–30 \text{ cm}^3 \)) measured during this interval are more typical of the magnetosheath (\( \approx 10–50 \text{ cm}^3 \)) than the mantle (\( \approx 1–5 \text{ cm}^3 \)) [Paschmann et al., 1976], suggesting Cluster may be very near the cusp.

Figures 5b–5e show the three components and magnitude of the proton velocity in GSM. The velocities exhibit considerable variability during the interval plotted. \( V_X \) fluctuates around zero before turning predominantly negative around 2100 UT. \( V_Y \) is predominantly positive throughout the interval plotted, gradually increasing from \( \approx 25 \text{ km s}^{-1} \) at 1930 UT to \( \approx 100 \text{ km s}^{-1} \) at the time of the \( B_Z \) reversals. \( V_Z \) is also mostly positive and generally increasing during the interval. The negative \( V_X \) and positive \( V_Z \) after 2130 UT are suggestive of the likely magnetosheath or mantle flow near the location of Cluster (i.e., antisunward and northward).

Figure 5e shows that the total velocity gradually increases from \( \approx 30 \text{ km s}^{-1} \) to \( \approx 100 \text{ km s}^{-1} \). Expected magnetosheath velocities are a few hundred kilometers per second in the region north of the cusp, so the measured velocities, with magnitude increasing outward, are more typical of the mantle.

Figure 5f shows \( V \) and \( V_A \) where \( V \) is the total proton velocity from Cluster-4 CIS/CODIF and \( V_A \) is the local Alfvén speed calculated using the CIS/CODIF proton density and the locally measured magnetic field magnitude at Cluster-4. During the first half of the interval, \( V_A \gg V \) indicating that Cluster is inside the magnetosphere. After 2100 UT, \( V_A \) decreases to \( \approx 100 \text{ km s}^{-1} \) reflecting the movement of Cluster into the higher-density, lower magnetic field region of the mantle.

The Cluster-4 CIS/CODIF observations largely support our conclusion from the magnetometer observations that the \( B_Z \) reversals occurred within the magnetosphere.
Figure 4. Twenty-two Hz (0.045 s) resolution magnetometer measurements from all four Cluster spacecraft for the Bz reversals a, b, c, and d. (a) Bx, (b) By, (c) Bz, (d) B.
The measured velocities indicate that we are close to the magnetopause and likely in the mantle. However, the observed densities are high for the mantle.

3.3. Cluster PEACE Observations

[19] Figure 6 displays electron differential energy flux spectrograms from Cluster 1 between 2030 and 2120 UT. Figure 6a shows the electron flux for 0°/C176 pitch angle, Figure 6b for 90°/C176 pitch angle, and Figure 6c for 180°/C176 pitch angle. The Cluster 1 B<sub>Z</sub> has been overlaid in black for reference. The first feature to note is that the electron fluxes at 0° and 180° pitch angle exceed the electron flux at 90° pitch angle. This indicates anisotropy in the electrons during the interval including the B<sub>Z</sub> reversals. There is also clear heating of the electrons at the times of the B<sub>Z</sub> reversals. The characteristic energy of the electrons is ~40 eV for the time interval plotted, increasing gradually to ~70 eV by 2120 UT. This may imply that Cluster is approaching the magnetosheath where typical electron energies are a few hundred eV. Note also that by 2120 UT the electron flux has become fairly isotropic.

[20] The peak fluxes prior to 2035 UT are at typical energies of 20–25 eV. However, at the time of the first B<sub>Z</sub> reversal from negative to positive the electron energy approximately doubles to ~50 eV. In the middle of the interval when B<sub>Z</sub> is positive, the electron flux decreases (2036 UT). As B<sub>Z</sub> passes through zero again the flux levels increase and exceed the flux level observed at the negative to positive reversal. Following the first B<sub>Z</sub> reversal the electron fluxes between 20 and 100 eV remain elevated and slightly energized compared to the time before 2035 UT. The characteristic energy is ~40 eV.
The second B\textsubscript{Z} reversal at \sim 2044 UT produces some heating but does not appear to cause an increase in flux. A flux decrease just after 2051 UT again produces heating but the flux remains fairly constant. The associated flux decrease for the positive B\textsubscript{Z} portion of the event is evident just before 2052 UT. The fourth B\textsubscript{Z} reversal at \sim 2100 UT shows heating but there is no clear flux drop during the positive B\textsubscript{Z} portion of the event. Less distinct B\textsubscript{Z} reversals at later times (e.g., \sim 2108 UT and 2115 UT) also are associated with identifiable signatures in the electrons.

3.4. ACE Solar Wind Observations

The vertical bars in Figure 3 indicate the times of the four B\textsubscript{Z} reversals observed at Cluster-1. The Cluster B\textsubscript{Z} has been overlaid for reference and the vertical black bars indicate the reversals in B\textsubscript{Z}. The solar wind IMF B\textsubscript{Z} is southward in the hours preceding the Cluster B\textsubscript{Z} reversals and remains southward at \sim 3 nT during the events. Assuming no problems with the selected time lag, the dawnward B\textsubscript{Y} during most of the interval implies that antiparallel merging can occur poleward of the subsolar point on closed field lines in the northern hemisphere and on the duskside in the southern hemisphere. However, the dominant component of the IMF during this interval is B\textsubscript{X} at \sim 6.5 nT, implying that the IMF is twisted radially toward the magnetosphere and this has implications for lobe merging. The solar wind speed is increasing during the interval of interest at Cluster. Finally, there is a gradual increase in dynamic pressure during the B\textsubscript{Z} reversals observed at Cluster. We will return to these solar wind observations when we discuss possible mechanisms for the Cluster B\textsubscript{Z} reversals.

4. Four-Point Observations

4.1. Discontinuity Analysis

The second B\textsubscript{Z} reversal at \sim 2044 UT produces some heating but does not appear to cause an increase in flux. A flux decrease just after 2051 UT again produces heating but the flux remains fairly constant. The associated flux decrease for the positive B\textsubscript{Z} portion of the event is evident just before 2052 UT. The fourth B\textsubscript{Z} reversal at \sim 2100 UT shows heating but there is no clear flux drop during the positive B\textsubscript{Z} portion of the event. Less distinct B\textsubscript{Z} reversals at later times (e.g., \sim 2108 UT and 2115 UT) also are associated with identifiable signatures in the electrons.

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using the multi-point Cluster measurements. At the time of these observations the maximum interspacecraft separation was ~500 kilometers. The reversal at ~2035:15 UT (Figure 4) was clearly observed by all four spacecraft. A number of characteristics are apparent from the four traces. Each spacecraft encounters the reversal at a different time, Cluster 3 observes the reversal first while Cluster 4 observes it last, the spacecraft exit the reversal in the order in which they entered it. The entrance and exit of the reversals is not symmetric, and wave activity was observed at each spacecraft after the initial $B_Z$ reversal. Note the previously discussed signatures in $B_X$, $B_Y$, and $B$ during the reversal.

Figure 7a displays only the $B_Z$ component from the four spacecraft and Figure 7b shows the spatial locations in GSM coordinates of each spacecraft when they encounter the first $B_Z$ reversal. The four panels show different spatial perspectives. Assuming the observed reversal is due to a discontinuity, we have used minimum variance analysis to determine the normal direction at each spacecraft. Minimum variance was applied for the time interval plotted in Figure 7a and the eigenvalues were typically in the ratio 100:10:1. The normal vector determined from minimum variance is plotted at each spacecraft location in Figure 7. The normal vectors at each spacecraft are the normal directions as determined from minimum variance.

Figure 7. (a) Twenty-two Hz (0.045-s) resolution magnetometer measurements of $B_Z$ reversal a for all four Cluster spacecraft. (b) GSM positions of the four Cluster spacecraft at the time each of the spacecraft observe the $B_Z$ reversal a. The vectors plotted at each spacecraft are the normal directions as determined from minimum variance.

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[25] We have used discontinuity analysis [Dunlop and Woodward, 1998] to determine the velocity at which the structures are moving. Times are referenced to an index time at which the reversal is first observed by one spacecraft. For our observations the reference spacecraft was Cluster 3. In order to determine whether the structure producing the $B_Z$ reversal is moving at a constant speed or is accelerating we plot the distance along the average normal direction...
between Cluster 3 and the other spacecraft against the time delays between observations at the spacecraft:

\[
\Delta r_n = \Delta r \cdot \hat{n}
\]

\[
\Delta t_i = t_i - t_{C3}
\]  

where \(\Delta r_n\) is the distance between a spacecraft and Cluster 3 along the normal direction, \(\Delta r\) is the distance between that spacecraft and Cluster 3 in GSM coordinates, \(\hat{n}\) is a unit vector in the normal direction averaged over all four Cluster spacecraft, \(t_i\) is the observation time of the B\(_Z\) reversal at Cluster \(i\) for \(i = 1, 2, 4\), and \(t_{C3}\) is the index time. Figure 8 displays \(\Delta r_n\) versus \(\Delta t_i\) for the four B\(_Z\) reversals indicated in Figure 2. Several items should be noted. All four Cluster spacecraft clearly observed the first B\(_Z\) reversal, whereas Cluster 4 did not observe the second or third reversals clearly. Additionally, the third B\(_Z\) reversal is ambiguous at Cluster 3. As a result, reliable \(\Delta r_n\) and \(\Delta t\) information from four spacecraft was acquired only for the first and second B\(_Z\) reversals. The first reversal provides the clearest evidence that the observed structure is moving with a constant speed, the points lying on a straight line with slope of \(~56\) km s\(^{-1}\). This is the order of magnitude of the flow speed measured by CIS (Figure 5), so the structures are apparently convected approximately with the background plasma. The speed calculated from the discontinuity analysis can be used to establish a scale size for the B\(_Z\) reversals. Each reversal typically lasts about 2 min. This corresponds to a scale size of \(~1\) R\(_E\).

### 4.2. Currents

The electric current density has been calculated from the four Cluster magnetometer data using the technique of Kepko et al. [1996] and Khurana et al. [1996, 1998]. Figure 9 shows \(J_1\) and the two perpendicular components \(J_{11}\) and \(J_{12}\) of the current density and the GSM magnetic field from Cluster 1 from 2030 to 2120 UT. The magnetic field prior to the first B\(_Z\) reversal at 2035 UT clearly shows that the parallel magnetic field direction is B\(_Z\) while B\(_X\) and B\(_Y\) comprise the perpendicular directions. The four B\(_Z\) reversals are indicated by the vertical lines. The negative to positive change in B\(_Z\) for reversal a is produced by a brief \((~30\) s\) large increase \((~80\) nA m\(^{-2}\)) in the perpendicular currents. During the positive B\(_Z\) portion of reversal a the perpendicular currents decrease to less than 10 nA m\(^{-2}\) while a prolonged parallel current peaks at \(~60\) nA m\(^{-2}\). This parallel current produces the decreases in B\(_X\) and B\(_Y\) visible around 2036 UT. Perpendicular currents increase again, but in a negative sense \((~40\) nA m\(^{-2}\)), as B\(_Z\) becomes negative again. The magnetic field and current density observations for reversal a indicate that Cluster passed through a spatially confined region where currents flowing perpendicular to the magnetic field produced a local reversal of B\(_Z\). Reversal b has a similar profile but the negative perpendicular currents are not present. Reversal c also has only positive perpendicular currents but no clear parallel current and the B\(_Y\) signature is positive rather than negative. This may indicate Cluster passed through only a part of the confined region where reversal c occurs. Reversal d is less organized than the first three reversals, with positive and negative parallel currents and both negative and positive B\(_X\).

### 5. Discussion

Field reversals of the type observed in the Cluster data of 23 February 2001 can in principle result either from
reconnection or from intermittent entry into a plasma regime of reversed field polarity. We consider several possible situations and their likelihood of producing the observed $B_Z$ field reversals. Figure 10a shows a schematic of the southward and northward $B_Z$ fields encountered along the Cluster trajectory in the northern dayside lobe.

5.1. Dynamic Pressure Effects

[28] The proximity of the Cluster spacecraft to the magnetosheath and the reversed orientation of $\mathbf{B}$ in the closed field line region equatorward of the polar cusp lead us to consider whether the $B_Z$ reversals arise from distortions of the magnetosphere that displace the magnetopause or the polar cusp. Figure 10b is a schematic that illustrates inward motion of the magnetopause in response to an increase of solar wind dynamic pressure, a process that could displace the magnetosheath to the location of the Cluster tetrad. Figure 3f shows the solar wind dynamic pressure for the time surrounding the $B_Z$ reversals. The dynamic pressure is increasing at the approximate time of the Cluster $B_Z$ reversals. The magnitude of the dynamic pressure changes is small and its change is unlikely to produce significant boundary displacement. The gradual increase observed is no more than 1–2 nPa above the nominal 2 nPa observed at 1 AU. In order to gauge the dynamic pressure increase necessary to move the magnetopause to the location of the Cluster spacecraft at 2035 UT we ran the T96 geomagnetic field model for dynamic pressures between 1 and 10 nPa. The model magnetopause moved inward and came close to the location of the Cluster spacecraft only with a dynamic pressure input of 10 nPa. Because the solar wind dynamic pressure (Figure 3f) remained well below the level needed to displace boundaries far from their nominal locations, we think it is unlikely that the Cluster spacecraft entered either the magnetosheath or the closed field line region of northward field equatorward of the cusp. This inference is supported by the flow velocities measured by the CIS instrument which does not observe clear magnetosheath plasma until after the $B_Z$ reversals have occurred. Support for this conjecture follows from noting that for a southward oriented solar wind $B_Z$ one expects a southward $B_Z$ in the magnetosheath. Consequently, it is unlikely that brief entries into the magnetosheath can account for the northward field reversals observed at Cluster.

5.2. Northward IMF $B_Z$

[29] Periods of northward IMF $B_Z$ are likely to produce lobe (i.e., poleward of the cusp) reconnection in the Northern Hemisphere. A reconnected northern lobe field line could produce a region of adjacent southward and northward $B_Z$ at the magnetopause (Figure 10c). If Cluster somehow crossed into this region of reconnected field lines, it is plausible that a northward $B_Z$ would be encountered.

Figure 9. (a) $J_{||}$, (b) $J_{\perp 1}$, (c) $J_{\perp 2}$, (d) Cluster 1 GSM $B_X$, (e) GSM $B_Y$, (f) GSM $B_Z$, (g) $B$. 
Whereas this mechanism offers a simple explanation for the $B_Z$ reversals, it is unlikely because of the consistently southward IMF $B_Z$ (Figure 3c) observed in the hours preceding and following the observations at Cluster. In addition, as Cluster moves outbound into the magnetosheath a predominantly northward magnetic field should have been observed if the IMF was northward. However, a small but predominantly negative $B_Z$ was observed as Cluster progressed into the magnetosheath. Therefore it is unlikely lobe reconnection during northward IMF was responsible for the $B_Z$ reversals at Cluster.

5.3. Intermittent Reconnection

[30] Intermittent reconnection could account for short intervals of reversed field. The negative IMF $B_Y$ and $B_Z$ rotate the symmetry axis of the shocked solar wind plasma in the magnetosheath away from the noon-midnight meridian (i.e., toward dawn in the Northern Hemisphere and toward dusk in the Southern Hemisphere). The magnetosheath flow is expected to diverge from the IMF symmetry axis and so the expected flow pattern is antisunward and duskward across much of the Northern Hemisphere magnetosphere (Figure 10d). This can account for the duskward and antisunward flow of CIS ions and the inferred motion of the regions of reversed magnetic field at the location of Cluster just prenoon. If reconnection occurs near the noon meridian in the high-latitude Southern Hemisphere with large negative IMF $B_Y$, one can anticipate a sharp bend in the duskside half of the reconnected field line whose foot is in the Northern Hemisphere. Ultimately, this flux tube must enter the northern lobe. Plasma flow will carry the kinked structure towards dusk and antisunward (path 1 in Figure 10d). The reconnected flux tube is then convected poleward in such a manner that the kink produced by reconnection is maintained as the magnetosheath flow carries it into the Northern Hemisphere. The outbound Cluster spacecraft in the northern mantle could, in principle, detect the kinked

**Figure 10.** (a) Schematic of the reversed $B_Z$ magnetic field regions observed by Cluster. (b) Movement of the magnetopause boundary due to dynamic pressure changes. (c) Lobe reconnection for northward IMF $B_Z$. (d) Rotation of the magnetospheric symmetry axis and possible reconnection geometry for negative IMF $B_Y$. The gray shaded circle indicates the position of Cluster. (e) Rotation of the magnetospheric symmetry axis and possible reconnection geometry for positive IMF $B_Y$. 

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flux tube as it reaches the northern lobe. A second possibility is the reconnected field line in the high-latitude Northern Hemisphere on the dayside. The reconnected field line whose foot is in the Northern Hemisphere could conceivably be convected poleward and duskward as the reconnection kink relaxes (path 2 in Figure 10d). However, as with the duskside connection in the Southern Hemisphere, it is difficult to envision this field line maintaining a northward \( B_Z \) by the time it reaches the position of Cluster.

Another scenario to consider is the reconnection geometry produced if the IMF \( B_Y \) is positive. As discussed in a previous section, the propagation uncertainty from ACE to the magnetopause forces us to consider the possibility that a greater time lag should have been used. If the delay time were taken as 2 hours, the lagged IMF \( B_Y \) would have been positive at the time of the Cluster \( B_Z \) reversals (Figure 3b at \( \sim2135 \) UT), even though the signs of IMF \( B_X \) and \( B_Z \) would have remained negative (we think that this large a shift is unlikely but explore its consequences). Positive IMF \( B_Y \) reverses the schematic shown in Figure 10d, reflecting it about the \( z \)-axis (Figure 10c). The antiparallel merging sites now develop on the dusk side in the Northern Hemisphere and on the dayside in the Southern Hemisphere. However, as with the negative IMF \( B_Y \) case, reconnected field lines in either hemisphere are not likely to have strong northward \( B_Z \) upon reaching the position of Cluster. This geometry is also unlikely because it predicts a positive \( B_Y \) at Cluster because of tail flaring, which is not observed (Figure 2b).

Particle signatures from PEACE are modified in and near the perturbed field region in ways consistent with reconnection. The pitch angle anisotropy of the electrons (i.e., higher fluxes at \( 0^\circ \) and \( 180^\circ \) than at \( 90^\circ \) (Figure 6)) indicates electrons are accelerated along the field, as expected in or near a reconnection region. The clear drop in the electron fluxes at the center of the \( B_Z \) reversals is also suggestive of reconnection. As the reconnected flux passes by the spacecraft, the higher-energy electrons will have already escaped the region, leaving lower-energy electrons to occupy the center of the structure. The particle signatures provide robust evidence for a reconnection scenario to explain the observed \( B_Z \) reversals. Furthermore, I. J. Rae et al. (manuscript in preparation, 2004), utilizing Super-DARN radar observations, present evidence for ionospheric transients coincident with the \( B_Z \) reversals observed at Cluster on 23 February. The Rae et al. study concludes that the ionospheric transients are due to flux transfer events, possibly linked to the signatures on which we report here. Although it is not hard to find regions on the magnetopause where reconnection may be occurring, the problem of explaining the persistence of a sharp kink in the field of the form suggested in Figure 10a remains unsolved.

Two other studies have utilized Cluster magnetometer data for the analysis of FTEs in February 2001. Owen et al. [2001] and Wild et al. [2001] analyzed apparent high latitude FTE signatures that closely resemble the low latitude signatures of FTEs. The events of 23 February 2001 do not have similar characteristics. However, we believe this is due to the fact that the Owen et al. and Wild et al. events occurred while Cluster was clearly on closed field lines. The events described here are very different in that they occurred while Cluster was on open field lines and the main component of the magnetic field (\( B_Z \)) reversed sign.

6. Conclusions

We have presented observations of quasi-periodic negative to positive reversals in \( B_Z \) observed by Cluster in the northern dayside mantle poleward of the cusp. The reversals (negative to positive) recur approximately every 8 min and occur in an otherwise negative \( B_Z \) background magnetic field. Observations (velocity and density) from the CIS instrument indicate Cluster is most likely located in the mantle and has not yet crossed the magnetopause. The electron observations from PEACE indicate heated electrons are associated with the \( B_Z \) reversals. The solar wind IMF, observed upstream at ACE, is southward but with a strong negative \( B_X \) for the entire interval of observation. The solar wind dynamic pressure increases gradually from \( \sim1.5 \) nPa to \( \sim3 \) nPa during the observations. Discontinuity analysis indicates the reversals are convected approximately with the background plasma and have a scale size of \( \sim1 \) R\(_E\). Current densities calculated from the four magnetometer data indicate that the \( B_Z \) reversals are associated with spatially enclosed currents perpendicular to the magnetic field. The combined observations are consistent with a reconnection scenario whereby a flux tube in the solar wind with large \( B_Y \) and significant negative \( B_Y \) reconnects with a closed magnetospheric flux tube on the dayside. The region of reconnection is uncertain and the maintenance of strongly northward field in the background (strongly southward) field has not been accounted for in our interpretation.

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References


Figure 6. (a) Cluster 1 PEACE LEEA/HEEA energy-time differential energy flux spectrogram of electrons at 0° pitch angle between 2030 and 2120 UT on 23 February 2001. The Cluster 1 B_Z has been overlaid for reference and the vertical black bars indicate the reversals in B_Z. (b) 90° pitch angle; (c) 180° pitch angle.