Cluster encounter of a magnetic reconnection diffusion region in the near-Earth magnetotail on September 19, 2003

A. L. Borg,[1] M. Øieroset,[2] T. D. Phan,[2] F. S. Mozer,[2] A. Pedersen,[1] C. Mouikis,[3] J. P. McFadden,[2] C. Twitty,[2] A. Balogh,[4] and H. Rème[5]

Received 13 June 2005; revised 3 August 2005; accepted 6 September 2005; published 13 October 2005.

[1] We report a clear encounter by the Cluster spacecraft of a magnetic reconnection diffusion region in the near-Earth magnetotail at $X_{GSM} = -17.5$ R_E on September 19, 2003. In addition to the reversals of the plasma jets and of GSM-z (∼normal) component of the magnetic field, clear signatures of Hall quadrupolar (GSM-y) magnetic fields as well as bipolar Hall (GSM-z) electric fields with amplitude up to 80 mV/m directed toward the neutral sheet in both hemispheres were observed. Furthermore, large fluctuations in the electric field perpendicular to the magnetic field with amplitudes reaching 65 mV/m were observed near the separatrices in both hemispheres and in association with local density minima. **Citation:** Borg, A. L., M. Øieroset, T. D. Phan, F. S. Mozer, A. Pedersen, C. Mouikis, J. P. McFadden, C. Twitty, A. Balogh, and H. Rème (2005), Cluster encounter of a magnetic reconnection diffusion region in the near-Earth magnetotail on September 19, 2003, *Geophys. Res. Lett.*, *32*, L19105, doi:10.1029/2005GL023794.

1. Introduction

[2] Magnetic reconnection is a universal plasma process which converts stored magnetic energy into particle energy and leads to topological changes. Reconnection takes place in a small diffusion region, but its consequences are large scale. While the consequences of reconnection can be studied outside the diffusion region, the understanding of the cause of reconnection requires observations inside the minuscule diffusion region.

[3] In the collisionless reconnection model, ions diffuse from the magnetic field in the ion scale diffusion region while electrons continue to move with the magnetic field and diffuse from the field later, in the smaller electron scale diffusion region. The separation of ions and electrons in the ion scale diffusion region creates a system of Hall currents which in turn induces Hall out-of-plane magnetic fields [*Sonnerup*, 1979] (Figure 1).

[4] The Hall current and magnetic field were first reported along the lobe/plasma sheet boundary away from the diffusion region [*Fujimoto et al.*, 1997; *Nagai et al.*, 2001]. Later on, a small number of fortuitous diffusion region encounters were reported where the Hall magnetic fields were observed. These events occurred in the distant magnetotail [*Øieroset et al.*, 2001], at the dayside magnetopause [*Mozer et al.*, 2002; *Vaivads et al.*, 2004], and in the near-Earth magnetotail [*Runov et al.*, 2003; *Asano et al.*, 2004; *Wygant et al.*, 2005].

[5] In addition to the Hall magnetic field, *Mozer et al.* [2002] and *Vaivads et al.* [2004] reported bipolar Hall electric fields directed toward (and normal to) the current sheet. Recently, *Wygant et al.* [2005] observed a bipolar GSE-y component of the electric field in the near-Earth plasma sheet which they interpreted as signatures of the Hall electric field. To be consistent with such a field in the *Wygant et al.* [2005] event, however, the current sheet needs to be twisted substantially such that the current sheet normal is directed close to GSM-y instead of the GSM-z direction.

[6] In this paper we present one of the clearest encounters of a diffusion region reported to date. The Cluster spacecraft detected all branches of the Hall quadrupolar field, as well as repeated encounters of the bipolar Hall electric field. Furthermore, large amplitude perpendicular electric field fluctuations were observed in the vicinity of the separatrices in association with density depletions. A remarkable feature of this event is that the current sheet coordinate system is close to the GSM coordinate system (with the current sheet lying approximately in the GSM x-y plane) so that the Hall electromagnetic fields are already evident in the GSM coordinate system without further data processing.

2. Observations and Analyses

2.1. Overview

[7] We study a flow reversal seen by Cluster around 23:30 UT on September 19, 2003. We use observations made by the Cluster plasma (CIS), the magnetic field (FGM), and the electric field (EFW) experiments. The Cluster tetrahedron was located at $(X, Y, Z)_{GSM} = (-17.5, 3.4, 0.6)$ R_E with internal separation distances of about 250 km. In this paper we establish the diffusion region encounter with measurements from spacecraft 4, the only spacecraft with full complements of plasma and field measurements on this day.

[8] Figure 2 shows ions (CIS), magnetic field (FGM), and electric field (EFW) data from 23:25:15 UT to 23:34:30 UT. The sampling rates for CIS, FGM and EFW for this event are 4s, 0.04s, and 0.04s, respectively. H^+ composition measurements from the CIS/CODIF sensor are employed for the plasma velocity measurements shown in Figures 2c–2e. Spacecraft 4 observed an interval of tailward (negative V_x) high speed flows up to ∼600 km/s followed by an interval of earthward (positive V_x) high speed flows up to ∼700 km/s. A

[1]Department of Physics, University of Oslo, Oslo, Norway.
[2]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[3]Space Science Center, University of New Hampshire, Durham, New Hampshire, USA.
[4]Space and Atmospheric Physics, Imperial College, London, UK.
[5]Centre d'Etude Spatiale des Rayonnements, Toulouse, France.

0094-8276/05/2005GL023794$05.00

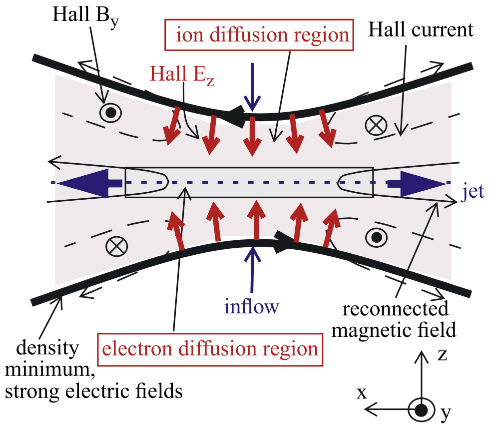

Figure 1. The geometry of the magnetic reconnection diffusion region with the results of the present observations included. A spacecraft passing through the diffusion region in the X direction should observe a reversal in the plasma jet direction as well as the Hall electromagnetic fields.

continuous reversal from negative to positive values of the plasma flow in the GSM X-direction (V_x) was observed from 23:29:00 UT to 23:30:15 UT with V_x passing through zero between 23:29:20 UT and 23:29:40 UT. The magnetic field Z component (B_z) was negative until 23:29:50 UT when it started to fluctuate around zero. After 23:30:50 UT B_z was mainly positive (Figure 2d). The near coincidence of the V_x and B_z reversals indicates that the spacecraft went from one side of the diffusion region to the other side, either through the diffusion region or through the inflow region.

[9] Spacecraft potential measurements calibrated with the PEACE electron density above 20 eV have been used to deduce the density shown in Figure 2b. Although the density occasionally dropped to below usual plasma sheet values it never reached values normally associated with the lobe. Also, the maximum energy in the ion spectrogram (Figure 2a) remained at plasma sheet values throughout the interval shown in Figure 2. Hence during the interval presented in Figure 2 Cluster remained inside the plasma sheet and did not encounter the lobe.

[10] The lone fact that Cluster remained in the plasma sheet throughout the flow reversal cannot be used as an indication that Cluster did not encounter the inflow region because reconnection may involve plasma sheet field lines. However, the velocity and magnetic field measurements indicate where the spacecraft was positioned relative to the reconnection region. If the spacecraft had encountered the inflow region while crossing the X-line we would expect to see a slow flow mainly in the Z direction, while V_x would be close to zero as Cluster moved from tailward to earthward flow. Furthermore, we would expect to see an excursion into a more stretched magnetic field configuration (increased $|B_x|$). From Figure 2c we see instead a gradual transition in V_x from negative to positive, as well as a stable B_x fluctuating around 15 nT (Figure 2f). Thus the spacecraft did not encounter the inflow region during the flow reversal, but went through the diffusion region instead.

[11] Minimum variance analysis of the magnetic field data for the 23:30:00–23:35:09 UT interval yields a current sheet normal of $(x,y,z)_{GSM} = (0.128, 0.131, 0.983)$. Thus the current sheet normal is within 10° of the GSM-z direction. Since the current sheet tilt of the present event is small we will describe the data in the GSM coordinate system. This avoids any uncertainties associated with the minimum variance direction determination. The fact that the Hall electromagnetic fields (presented in the next sections) are well organized in GSM provides further evidence that the current sheet tilt is small.

2.2. Hall Magnetic Field

[12] In this section we investigate the occurrence of the Hall quadrupolar magnetic fields in the region that we have interpreted as the diffusion region. The occurrence of such fields would further validate the diffusion region encounter interpretation. The fact that the spacecraft encountered tailward and earthward flow regions as well as both northern ($B_x > 0$) and southern ($B_x < 0$) hemispheres means that the spacecraft should detect all 4 branches of the Hall quadrupolar fields (see Figure 1).

[13] Figure 3 shows B_x versus v_x with B_y data represented as circles for the 23:25:15 UT–23:34:00 UT interval (the

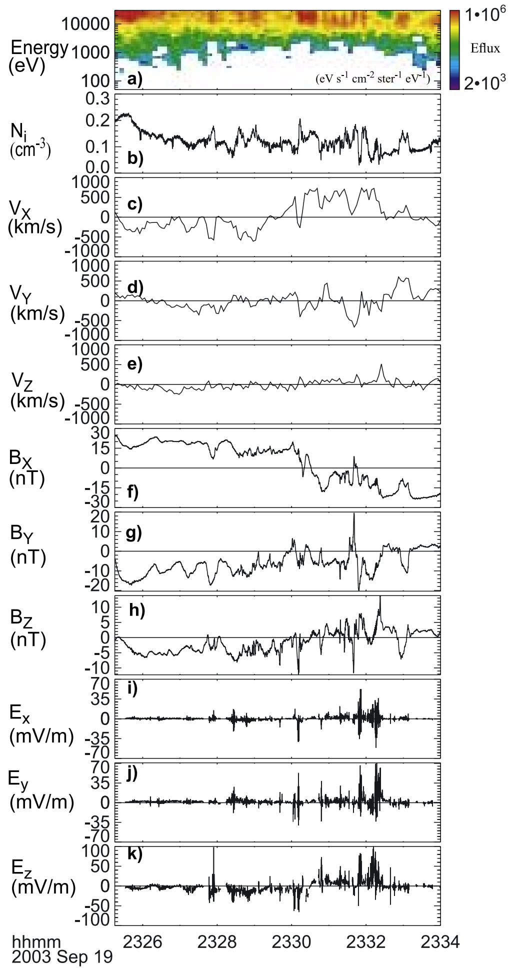

Figure 2. Cluster spacecraft 4 observations on September 19, 2003 for the 23:25:15–23:34:00 UT interval. (a) H^+ spectrogram from CODIF; (b) density converted from spacecraft potential; (c)–(e) CODIF H^+ velocity (GSM); (f)–(h) magnetic field (GSM); (i)–(k) electric field (GSM). Cluster was located at $(X,Y,Z)_{GSM} = (-17.5, 3.4, 0.6)\ R_E$.

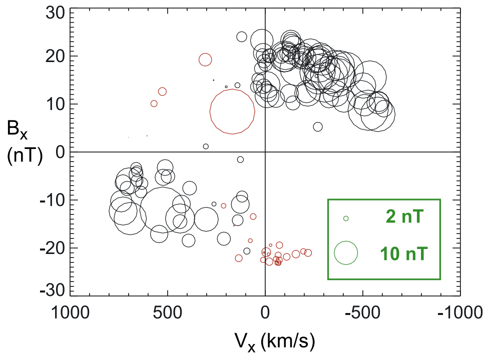

Figure 3. B_x versus v_x with B_y represented as circles for the 23:25:15 UT–23:34:00 UT interval (the interval plotted in Figure 2). A black circle indicates a negative value B_y and a red circle a positive value, with the circle size being relative to the size of B_y. Note the sign of V_x.

same interval as plotted in Figure 2). A black circle indicates a negative value B_y and a red circle a positive value, with the circle size being relative to the size of B_y. It is seen that the black circles (negative B_y) appear predominantly in the positive B_x-negative V_x and negative B_x-positive V_x quadrants, while the red circles (positive B_y) are predominantly in the remaining two quadrants. This behavior is consistent with the Hall magnetic field pattern. A small number of data points occur in the wrong quadrant, but these are mostly B_y data of low magnitude. One also notes an asymmetry in the size of B_y, with B_y much larger (in magnitude) in the positive B_x-negative V_x and negative B_x-positive V_x quadrants than the other 2 quadrants. This asymmetry may be due to the presence of a (small) guide field as seen in some simulations [e.g., *Daughton and Karimabadi*, 2005], but it could also be due to the smaller number of samples in the two quadrants that show smaller B_y.

[14] The maximum angle between the high latitude (outside the diffusion region) magnetic fields in the northern and southern hemisphere is 175° (samples taken at 23:25:17 UT and 23:33:19 UT). Thus the guide field (the non-antiparallel (Y_{GSM}) component of the magnetic field in the inflow region) in this event is less than ~4% of the anti-parallel field (25 nT). If a 1 nT guide field is subtracted from the B_y values plotted in Figure 3, it does not change the picture qualitatively.

[15] Finally, the amplitude of the observed Hall B_y field is ~13–18 nT, i.e., ~50–75% of the total magnetic field.

2.3. Electric Field in the Vicinity of the Diffusion Region

[16] Figures 2i–2k show the 3 components of the electric field in GSM. Cluster measures 2 components of the electric field in the spin plane. The third component (E_z) is derived by assuming that the electric field component parallel to the magnetic field is zero: $E_z = -E_xB_x/B_z - E_yB_y/B_z$. To minimize errors in the derivation of E_z due to weak magnetic fields or large ratios of B_x/B_z and B_y/B_z, E_z in Figure 2k is constructed by requiring that $|B| > 1$ nT and B_x/B_z and B_y/B_z be less than 10. These criteria lead to small gaps in the electric field time series shown. The $E \cdot B = 0$ assumption would be violated in the narrow electron-scale region where $E_\parallel \neq 0$, but the assumption does not affect ion-scale processes discussed in this paper.

[17] Figures 2i–2k show that there are brief occurrences of large (larger than 25 mV/m) electric fields in the 23:28:20–23:32:20 UT interval. The E_x and E_y fields fluctuate between positive (up to 65 mV/m) and negative (up to 50 mV/m) values whereas E_z is much more organized and changes sign from almost exclusively negative (up to 65 mV/m) to positive (up to 80 mV/m) as the spacecraft moves from the northern to the southern hemisphere (as seen in B_x in Figure 2f). In other words, E_z is directed toward the center of the current sheet in both hemispheres. This finding is investigated further in Figure 4a, which shows that the large E_z values occur for $|B_x|$ = 10–13 nT, i.e. at intermediate latitudes, but not in the center of the current sheet ($B_x = 0$). The E_z behavior is consistent with the predicted Hall electric field where $\mathbf{E}_z = -\mathbf{v}_{e,y} \times \mathbf{B}_x$. It is remarkable that this well-defined (in terms of its sign) field is not measured directly, but is constructed (with the $\mathbf{E} \cdot \mathbf{B} = 0$ assumption) from the much more fluctuating E_x and E_y fields. Even more remarkable is the fact that although there are fluctuations in the magnitude of E_z, the sign of E_z is extremely well defined even in the high resolution (0.04 s) data. In contrast to the *Wygant et al.* [2005] event where the Hall electric field was reportedly seen over 4 seconds, the Hall E_z in our event is observed repeatedly over a period of 4 minutes. According to theory [*Shay et al.*, 1998; *Pritchett*, 2005] (and in agreement with our observations), this Hall electric field develops in the ion scale diffusion region, where the ions are unmagnetized but the electrons are still frozen-in. The $\mathbf{V}_{e,y} = \mathbf{E}_z \times \mathbf{B}_x/B^2$ drift and its pulling of the magnetic field in the negative y direction results in the quadrupolar Hall B_y.

[18] Turning now to E_x and E_y, in Figures 2i and 2j, large amplitude fluctuations in these electric field components occur repeatedly, reaching values up to 65 mV/m in E_x and

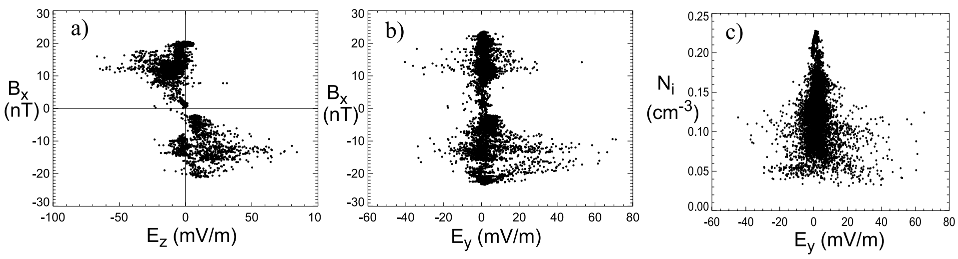

Figure 4. Scatterplots for the 23:25:15 UT – 23:34:00 UT interval (the interval plotted in Figure 2: (a) B_x versus E_z; (b) B_x versus E_y; (c) Density versus E_y.

E_y. These fields fluctuate with periods in the 0.15–0.5 seconds range. Figure 4b shows that the large amplitude values of E_y occur at large (10–20 nT) positive and negative values of B_x. In other words they occur on average at larger distances from the current sheet mid-plane than the large E_z values. Comparing electric field and density in the interval 23:25:15 UT–23:34:00 UT in Figure 4c, we see that the largest values of E_y occur at low densities. This feature is even more striking in the time series (Figure 2). Large E_x and E_y coincide with brief dips in the plasma density. The occurrence at large B_x and in density dips suggest that these large electric fields are located in the vicinity of the separatrices. In simulations, density depletions are found in the vicinity of the separatrices due to enhanced magnetic field strength generated by the Hall current [*Shay et al.*, 2001].

[19] The observed large E_x and E_y in the density cavities at the edges of the current sheet may be similar to the field observed by *André et al.* [2004] at the dayside magnetopause. But in contrast to the dayside magnetopause events where such fields and density cavities are only apparent on the magnetospheric side of the current sheet, these fields are observed in the present event on both sides of the current sheet, i.e., in both hemispheres. (see Figure 4b). Furthermore, the dayside events were observed far from the diffusion region [*André et al.*, 2004] whereas here the observations were made in the vicinity of the diffusion region. This suggests that the density depletion and intense electric field extend from the diffusion region to large distances away, along the separatrices.

3. Summary

[20] We have presented Cluster plasma and field observations which establish one of the clearest encounters with a diffusion region reported to date. What makes this event remarkable is its simplicity. The current sheet tilt in this event is small so that the reconnection flow and Hall electromagnetic fields are already apparent in the GSM coordinate system without the need to transform the data into a different current sheet coordinate system. The guide field for this event is ~4% of the anti-parallel field. The key observations are:

[21] 1. A reversal of V_x from negative to positive (Figure 2c) coincided with a reversal in B_z from negative to positive (Figure 2h).

[22] 2. The V_x reversal was continuous (i.e., without an interval of near-zero V_x) and there was no excursion into a more stretched magnetic field configuration, indicating that the spacecraft did not enter the inflow region, but remained inside the reconnection layer during the transit from one side of the X-line to the other.

[23] 3. Out-of-plane Hall magnetic field (B_y) was observed in all four quadrants of the reconnection geometry (Figure 3), but an unexplained asymmetry in magnitude is seen.

[24] 4. Repeated (and consistent) detections of negative E_z in the northern hemisphere and positive E_z in the southern hemisphere are consistent with the occurrence of Hall electric fields pointing toward the current sheet (Figure 4a). The large amplitude of E_z and its well-defined sign (even at 0.04 s resolution), together with the fact that the Hall E_z is repeatedly detected imply that this field cannot be missed by spacecraft traversing the diffusion region.

[25] 5. Large amplitude electric fields were observed during the diffusion region crossing. The strong electric fields occurred at high latitudes (Figure 4b) and for low densities (Figure 4c). We interpret this as the strong electric fields being located along the separatrices, where the density has been shown to have a minimum [*Shay et al.*, 2001]. As opposed to the dayside magnetopause cases where strong electric fields have been observed only on the magnetospheric side of the current sheet and far away from the diffusion region [*André et al.*, 2004], we observed large amplitude electric fields on both sides of the current sheet and in the vicinity of the diffusion region in the near-Earth tail.

[26] **Acknowledgments.** We thank Jim Drake for helpful discussions. This work was performed while A. L. Borg was visiting UC Berkeley on a Kristine Bonnevie scholarship from the Faculty of Mathematics and Natural Sciences, University of Oslo, Norway. This work has been supported by the Research Council of Norway and funded in part by NASA grants NAG5-12941, NNG05GE30G, and FDNAG5-11944 at UC Berkeley.

References

André, M., et al. (2004), Thin electron-scale layers at the magnetopause, *Geophys. Res. Lett.*, *31*, L03803, doi:10.1029/2003GL018137.

Asano, Y., et al. (2004), Current sheet structure around the near-Earth neutral line observed by Geotail, *J. Geophys. Res.*, *109*, A02212, doi:10.1029/2003JA010114.

Daughton, W., and H. Karimabadi (2005), Kinetic theory of collisionless tearing at the magnetopause, *J. Geophys. Res.*, *110*, A03217, doi:10.1029/2004JA010751.

Fujimoto, M., et al. (1997), Observations of earthward streaming electrons on the trailing boundary of a plasmoid, *Geophys. Res. Lett.*, *24*, 2893–2896.

Mozer, F. S., S. D. Bale, and T. D. Phan (2002), Evidence of diffusion regions at a subsolar magnetopause crossing, *Phys. Rev. Lett.*, *89*, doi:10.1103/PhysRevLett.89.015002.

Nagai, T., et al. (2001), Geotail observations of the Hall current system: Evidence of magnetic reconnection in the magnetotail, *J. Geophys. Res.*, *106*, 25,929–25,950.

Øieroset, M., et al. (2001), In situ detection of collisionless reconnection in the Earth's magnetotail, *Nature*, *412*, 414–417.

Pritchett, P. L. (2005), Onset and saturation of guide-field magnetic reconnection, *Phys. Plasmas*, *12*, 062301.

Runov, A., et al. (2003), Current sheet structure near magnetic X-line observed by Cluster, *Geophys. Res. Lett.*, *30*(11), 1579, doi:10.1029/2002GL016730.

Shay, M. A., et al. (1998), Structure of the dissipation region during collisionless magnetic reconnection, *J. Geophys. Res.*, *103*, 9165–9176.

Shay, M. A., et al. (2001), Alfvénic collisionless magnetic reconnection and the Hall term, *J. Geophys. Res.*, *106*, 3759–3772.

Sonnerup, B. U. Ö. (1979), *Solar System Plasma Physics*, vol. III, edited by L. T. Lanzerotti, C. F. Kennel, and E. N. Parker, pp. 45–108, Elsevier, New York.

Vaivads, A., et al. (2004), Structure of the magnetic reconnection diffusion region from four-spacecraft observations, *Phys. Rev. Lett.*, *93*, doi:10.1103/PhysRevLett.93.105001.

Wygant, J. R., et al. (2005), Cluster observations of an intense normal component of the electric field at a thin reconnecting current sheet in the tail and its role in the shock-like acceleration of the ion fluid into the separatrix region, *J. Geophys. Res.*, *110*, A09206, doi:10.1029/2004JA010708.

A. Balogh, Space and Atmospheric Physics, Imperial College, London SW7 2BZ, UK.

A. L. Borg and A. Pedersen, Department of Physics, University of Oslo, N-0316 Oslo, Norway. (a.l.borg@fys.uio.no)

J. P. McFadden, F. S. Mozer, M. Øieroset, T. D. Phan, and C. Twitty, Space Sciences Laboratory, University of California, Berkeley, Berkeley, CA 94720, USA.

C. Mouikis, Space Science Center, University of New Hampshire, Durham, NH 03824–3535, USA.

H. Rème, Centre d'Etude Spatiale des Rayonnements, F-31028 Toulouse, France.