

## Observations of multiple X-line structure in the Earth's magnetotail current sheet: A Cluster case study

J. P. Eastwood,<sup>1</sup> D. G. Sibeck,<sup>1</sup> J. A. Slavin,<sup>1</sup> M. L. Goldstein,<sup>1</sup> B. Lavraud,<sup>2</sup> M. Sitnov,<sup>3</sup> S. Imber,<sup>4</sup> A. Balogh,<sup>4</sup> E. A. Lucek,<sup>4</sup> and I. Dandouras<sup>5</sup>

Received 19 January 2005; revised 15 March 2005; accepted 14 April 2005; published 11 June 2005.

[1] Observations of the Earth's magnetotail made by the four Cluster spacecraft on October 2 2003 are presented. Multi-spacecraft analysis is used to show that the variations in field and flow observed in the vicinity of the magnetotail current sheet are most consistent with a series of two active reconnection sites bounding an Earthward moving flux rope. We demonstrate that a single spacecraft analysis of the same data leads to the incorrect conclusion that a single X-line is moving tailward. The implications of this in relation to the interpretation of single spacecraft observations are outlined. These results show that reconnection can occur simultaneously at different points in the near-Earth magnetotail current sheet, providing (further) important experimental validation of multiple X – line reconnection theories on the mesoscale (tens of ion inertial length) level.

**Citation:** Eastwood, J. P., D. G. Sibeck, J. A. Slavin, M. L. Goldstein, B. Lavraud, M. Sitnov, S. Imber, A. Balogh, E. A. Lucek, and I. Dandouras (2005), Observations of multiple X-line structure in the Earth's magnetotail current sheet: A Cluster case study, *Geophys. Res. Lett.*, *32*, L11105, doi:10.1029/2005GL022509.

### 1. Introduction

[2] It is widely accepted that the dynamics of the Earth's magnetosphere are driven mainly by the solar wind through reconnection at the magnetopause and in the magnetotail [e.g., Kennel, 1995]. In the simplest conceptual picture [Dungey, 1961], reconnection at the dayside magnetopause under solar wind conditions dominated by southward interplanetary magnetic field (IMF) adds open magnetic flux to the magnetotail. The amount of open flux cannot indefinitely increase; after some time, reconnection across the magnetotail current sheet reduces the open flux, converting magnetic energy into plasma kinetic and thermal energy. This picture has evolved into what is now known as the Near Earth Neutral Line (NENL) model [e.g., Baker et al., 1996], in which a distant neutral line  $\sim 100$  Earth radii (Re) from the Earth [Slavin et al., 1985] causes open magnetic flux to reconnect to the nightside magnetosphere. This flux resists compression as it convects closer to the Earth; the

system is thought to relax by reconnecting at a near-Earth neutral line 20–30 Re downtail [Nagai et al., 1998], causing the formation of a tailward moving plasmoid [e.g., Hones, 1977; Slavin et al., 2002].

[3] Magnetotail reconnection predicts that high-speed Earthward and tailward flows should be correlated with northward and southward magnetic fields [Baumjohann et al., 1990; Angelopoulos et al., 1992]. This has been used, for example, to determine the distribution of magnetic X – lines [Ueno et al., 1999]. Reported observations of the reconnection site itself have concentrated on the existence of quadrupole magnetic field structure and other phenomena caused by Hall effect physics [Øieroset et al., 2001; Nagai et al., 2001; Runov et al., 2003; Deng et al., 2004].

[4] The basic NENL model does not account for certain magnetospheric phenomena, for example earthward moving flux ropes in the near-Earth magnetotail [Elphic et al., 1986; Moldwin and Hughes, 1994; Slavin et al., 2003a; Zong et al., 2004; Deng et al., 2004]. Earthward moving flux ropes are typically only a few Re in size (i.e., tens of ion inertial lengths,  $c/\omega_{pi}$ ) and are therefore smaller than the tailward moving plasmoid in the NENL model. They have also been used to explain Traveling Compression Regions (TCRs) exhibiting a southward/northward (S/N) perturbation of the magnetic field [Slavin et al., 2003a]. More recent work from Cluster has shown that earthward moving TCRs are not only a common occurrence in the near tail, but can also occur several times in a single 'event' [Slavin et al., 2005].

[5] The Earthward moving flux ropes and associated S/N TCRs are most easily explained by the existence of multiple reconnection X – lines, forming magnetic islands on the mesoscale (tens of  $c/\omega_{pi}$ ) level [e.g., Slavin et al., 2003a]. As argued by Schindler [1974], the rate of reconnection at each X – line will not necessarily be the same; consequently, once the point of fastest reconnection begins to process the outer plasma sheet and lobe flux tubes, everything Earthward of this point will be swept up Earthward. This has also been investigated by Ohtani et al. [2004] who showed simulations predicting breakup of the current sheet on scales of tens of  $c/\omega_{pi}$ . Although there is numerical and experimental evidence suggesting that current sheet filamentation and multiple X – line reconnection does occur, we are unaware of any observations of the early stages of this process or of any reports indicating that reconnection may occur at multiple sites, simultaneously, in the near-Earth magnetotail.

[6] Here, Cluster data are presented that appear to show the existence of convective plasma flow arising simultaneously from two topologically different sites. These sites

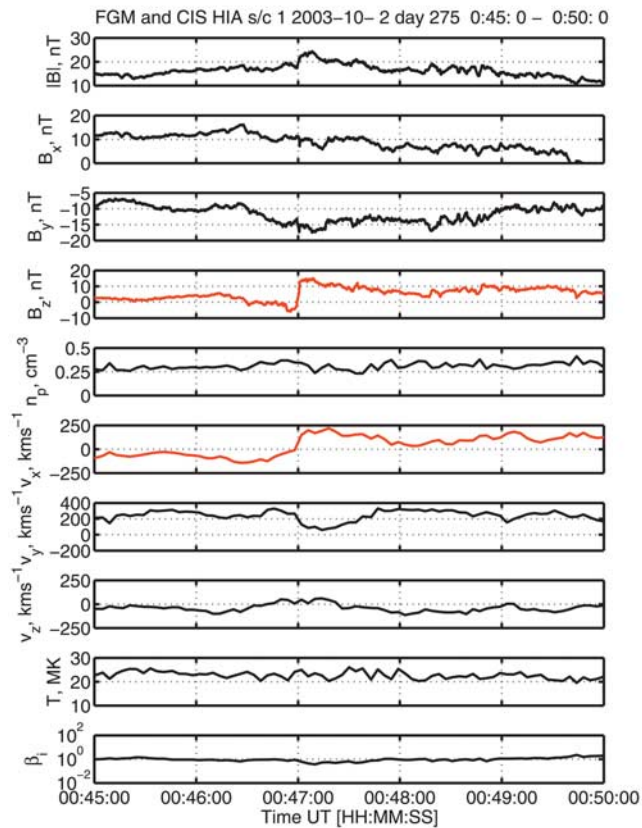
<sup>1</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

<sup>2</sup>Los Alamos National Laboratory, Los Alamos, New Mexico, USA.

<sup>3</sup>Institute for Research in Electronic and Applied Physics, University of Maryland, College Park, Maryland, USA.

<sup>4</sup>The Blackett Laboratory, Imperial College London, London, UK.

<sup>5</sup>Centre d'Etude Spatiale des Rayonnements/Centre National de la Recherche Scientifique—Université Paul Sabatier, Toulouse, France.



**Figure 1.** Plasma and magnetic field data from Cluster 1, from 2 October 2003, 00:45UT–00:50UT. The top four panels show the field magnitude and the three components of the field in GSM coordinates, obtained from Cluster FGM at 22 vector/s resolution. Subsequent panels show the plasma density, three components of the plasma velocity, the plasma temperature and the plasma beta at 4 s resolution.

bound an Earthward moving flux rope. The picture that arises from these observations adds to the evidence supporting the existence of current sheet filamentation in the near-Earth magnetotail. A single spacecraft analysis of the same data leads to a different conclusion about the inferred spatial structure. This demonstrates the main problem in single spacecraft analysis: the difficulty in disentangling time variation from spatial structure and plasma flow.

## 2. Observations

[7] Data from the Cluster Flux-Gate Magnetometer (FGM) [Balogh *et al.*, 2001] and Cluster Ion Spectrometry (CIS) Hot Ion Analyzer (HIA) [Rème *et al.*, 2001] instruments are presented. Figure 1 shows data from Cluster 1 obtained on October 2, 2003, between 00:45UT and 00:50UT. The top four panels show the magnetic field at 22 vector/s resolution in Geocentric Solar Magnetic (GSM) coordinates. Subsequent panels show the ion density, the components of the plasma velocity in GSM coordinates, the plasma temperature, and the ion plasma beta. The spacecraft entered the plasma sheet ( $\beta \sim 1$ ) shortly after midnight, and remained there until at least 06UT. 10 minutes after this event, very fast earthward plasma flows and reduced

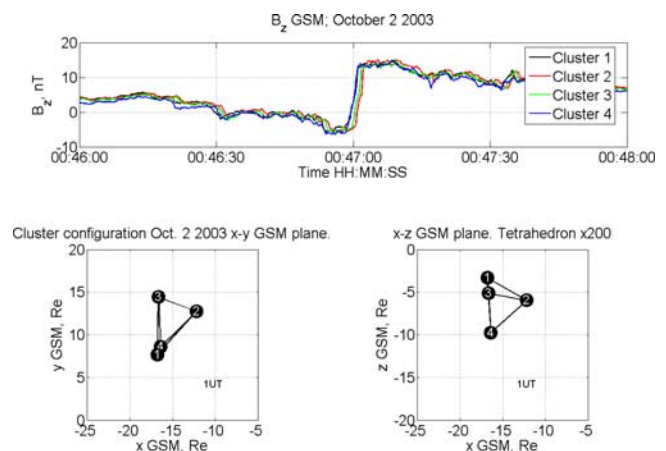
densities were observed. Subsequently, the spacecraft resided near the neutral sheet ( $B_x \sim 0$ ) for several hours.

[8] At 00:47UT,  $B_z$  rapidly changed from southward to northward. This was accompanied by a reversal in  $v_x$  from negative to positive (these time series are highlighted in red). This change is often associated with an X – line moving tailward with respect to the spacecraft [e.g., Ueno *et al.*, 1999]. We note that the plasma beta remained constant at a relatively high value ( $\beta \approx 1$ ) indicating that the spacecraft were deep in the plasma sheet [Slavin *et al.*, 1985; Baumjohann *et al.*, 1990].  $B_x$  remained positive, implying that the spacecraft did not approach the current sheet itself, remaining in the northern half of the magnetotail.

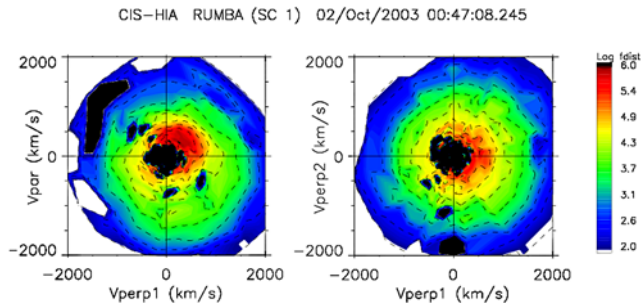
[9] Figure 2 (top) shows  $B_z$  in the interval 00:46UT–00:48UT. The colors black, red, green and blue are used to distinguish Cluster 1, 2, 3 and 4. Cluster 2 is the last spacecraft to encounter the reversal in  $B_z$ . Figure 2 (bottom left, right) shows the configuration of the Cluster tetrahedron (magnified  $\times 200$  relative to Cluster 1) at 01:00UT projected into the x-y and x-z GSM planes. The spacecraft separation was  $\sim 300$  km. Cluster 2 was located closest to the Earth. Qualitatively, it can be seen that the reversal in  $B_z$  was moving earthwards, not tailwards. Consequently, this feature does not correspond to a tailward moving X – line.

[10] To understand this event in more detail, a multi-spacecraft timing analysis [e.g., Schwartz, 1998] was applied to the magnetic field data. The time at which each spacecraft crossed  $B_z = 0$  was used to estimate the normal to the plane  $B_z = 0$ , and the normal speed. The technique assumes that the structure moves at constant velocity and that the surface  $B_z = 0$  is planar on the scale of the spacecraft tetrahedron. In a simple X – line configuration, this plane would contain the neutral line and be perpendicular to the reconnection jets. The normal speed was found to be  $140 \pm 13$  km/s along  $\mathbf{n} = [0.778 \ 0.595 \ 0.158]$  GSM.

[11] These results were used to transform the plasma data into a frame co-moving with the magnetic field structure. A flow reversal tailward/Earthward was still observed in this



**Figure 2.** (top) The  $B_z$  component of the magnetic field observed by all four Cluster spacecraft in the interval 00:46UT–00:48UT on 2 October 2003. The data resolution is 22 vectors/s. (bottom) The projection of the Cluster tetrahedron into the GSM x-y and x-z planes. The tetrahedron is magnified by a factor of 200. Cluster 1 is in the correct position.



**Figure 3.** Cuts of the 3D ion distribution observed by Cluster 1 CIS – HIA at 00:47:08UT, on 2 October 2003. (left) The vertical axis is aligned to the magnetic field, and the horizontal axis is perpendicular to the field, such that the maximum phase space density is contained in this plane. (right) A cut through the plane perpendicular to the magnetic field, where  $v_{\parallel} = 0$ .

frame, but since the structure was found to be moving Earthwards, the magnitude of the tailward flow was larger. The flow parallel to  $\mathbf{B}$  was found to be  $\sim 200 \text{ km s}^{-1}$  in this frame, switching off briefly during the field reversal. The moments are consistent with convective flows in the vicinity of the field reversal, superimposed on a cross tail streaming component. The existence of the parallel velocity component is explained by the large  $|B_y|$ . During this interval,  $B_y \sim -10$  to  $-15 \text{ nT}$ . Given that Cluster was located in the near-Earth magnetotail, at a range of  $\sim 19 \text{ Re}$  from the Earth, this is exceptionally large. At 00:00UT, ACE, at the L1 point upstream of Earth measured  $\mathbf{B}_{\text{IMF}} = (10.6, -14.5, -3.0)$ . The IMF  $B_y$  was large for several hours before this time, and the large  $|B_y|$  in the magnetotail is likely to be explained by this, although more detailed modeling is required to understand the extent to which the IMF is mapped into the tail [see, e.g., Cowley, 1981].

[12] Observations of the ion distributions are essential to confirm the absence of multiple co-existing populations or beams, which would render the moments misleading. During this interval, CIS – HIA recorded the full 3d distributions at 12 s resolution. The ion distributions in the interval 00:46:20–00:48:20 were examined, and throughout most of the interval, the distributions exhibited a single peak. After 00:48:00, a secondary counter-streaming population began to appear. The distributions just before and after the field reversal exhibited significant convective components. Figure 3 shows the distribution recorded by Cluster 1 at 00:47:08, shortly after the reversal in  $B_z$ . There is a single maximum in the distribution; this peak is not confined to  $V_{\text{par}}$ , the field-aligned axis. Consequently, the moments may be used to accurately describe the plasma properties, and there is a significant convective component.

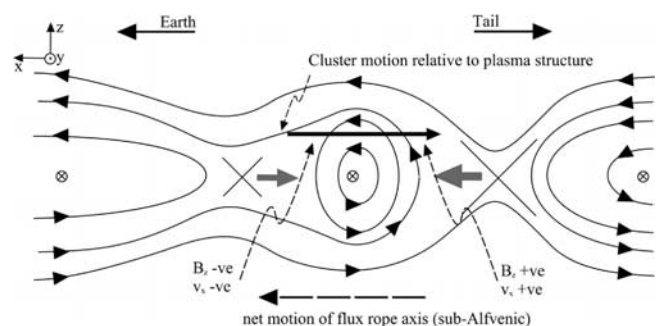
### 3. Discussion

[13] Single spacecraft observations of southward field and tailward flow followed by northward field and earthward flow have been interpreted as the signature of a single X-line moving away from the Earth over the observing spacecraft. The results presented here demonstrate that this

is not always the case. Overall, we observe an earthward moving feature. Since  $B_z$  first points southward, then northward, and there is a substantial  $B_y$ , this implies a twisting of the magnetotail. The similarity to signatures previously reported suggests a flux rope type topology [Elphic *et al.*, 1986; Hughes and Sibeck, 1987; Slavin *et al.*, 2003a, 2003b]. Given the time taken for the event to elapse, we calculate that the flux rope has a scale of a few  $\text{Re}$  ( $30\text{--}50 \text{ c}/\omega_{\text{pi}}$ ). This is compatible with the results of simulations, which show the fragmentation of current sheets into islands on similar scales.

[14] The center of this structure is preceded by tailward flow, and followed by Earthward flow. This is illustrated in Figure 4. The flows are sourced from different regions. Since the two plasma flows are convective, we interpret them as being sourced from reconnection sites. It is unlikely that Cluster observed one flow stop as the other started; it is perhaps more likely that both flows were being generated simultaneously. Also, recent theoretical work suggests that a Y-line may form (for small  $B_y$ ) on the Earthward side (M. Sitnov, private communication). Further work is required to establish if this is in fact the case.

[15] The flux rope is injected with magnetic flux and plasma from both sides. The magnetic field strength is enhanced inside the flux rope. Also, the earthward flows are larger than the tailward flows. It may be the case that the tailward X – line is stationary relative to the spacecraft, and pushes the earthward X – line towards the earth as the flux rope grows. This would cause the structure to move over the spacecraft in a manner consistent with the observations. Alternatively, there may be another X – line further tailward, pushing both the X – lines and the flux rope Earthward. The fact that Cluster did not observe the jets on the other sides of the proposed X – lines may be due to the relative motions of the plasma and the spacecraft, or the time dependent nature of the processes. Furthermore, we have yet to establish a significant quadrupole perturbation in the  $B_y$  component of the magnetic field. It may be the case that the spacecraft are too far from the proposed X – lines to observe this perturbation. Nevertheless, the conclusion that the two flows arise from physically different locations cannot be avoided. Finally, we point out that there is a



**Figure 4.** Event interpretation. The plot is shown in the  $x$ - $z$  plane, such that the Earth is to the left ( $x \sim$  timing normal). An earthward moving flux rope signature has been observed, bound by oppositely directed flows. The observed flows, shown in gray, must arise from topologically different sites. The reconnection flow from the tailward site is larger. The core field points into the page.

significant  $v_y$ , which is suppressed for a short time after the change in  $B_z$  is observed. Changing the coordinate system to one based on the average magnetic field and the calculated normal (which is nearly perpendicular to the average field) shows that this flow largely represents the parallel component of the plasma motion. Figure 4 is therefore a simplified 2d picture of the overall 3d plasma behavior. Further study is required to fully understand the 3d nature of the plasma flow.

#### 4. Conclusions

[16] Observations of Cluster magnetic field and plasma data recorded in the magnetotail have been presented. Based on a single spacecraft analysis, the hypothesis that a southward field and tailward flow followed by a northward field and earthward flow is a tailward moving X – line has been shown, in this case, to be incorrect. Multi-spacecraft analysis has shown that this feature is moving Earthward, and moreover appears to be a flux rope-type structure. This leads to the conclusion that magnetic reconnection was occurring at two different sites in the near-Earth magnetotail current sheet at the same time, both of which were contributing to the growth of the flux rope. In particular previous single spacecraft analyses may be open to reinterpretation, and further work is underway surveying the Cluster dataset for similar features in order to assess the extent to which this result is representative.

[17] **Acknowledgments.** This work was performed while JPE held a National Research Council Resident Research Associateship Award at NASA GSFC. We would like to thank J. Drake and M. Shay of the University of Maryland and M. Hesse of NASA/GSFC for useful discussions. This work was supported in part by the NASA guest investigator program.

#### References

- Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pellat, R. J. Walker, H. Lühr, and G. Paschmann (1992), Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res.*, *97*, 4027–4039.
- Baker, D. N., T. I. Pulkkinen, V. Angelopoulos, W. Baumjohann, and R. L. McPherron (1996), Neutral line model of substorms: Past results and present view, *J. Geophys. Res.*, *101*, 12,975–13,010.
- Balogh, A., et al. (2001), The Cluster magnetic field investigation: Overview of inflight performance and initial results, *Ann. Geophys.*, *19*, 1207–1217.
- Baumjohann, W., G. Paschmann, and H. Luhr (1990), Characteristics of high-speed ion flows in the plasma sheet, *J. Geophys. Res.*, *95*, 3801–3809.
- Cowley, S. W. H. (1981), Magnetospheric asymmetries associated with the y-component of the IMF, *Planet. Space Sci.*, *29*, 79–96.
- Deng, X. H., H. Matsumoto, H. Kojima, T. Mukai, R. R. Anderson, W. Baumjohann, and R. Nakamura (2004), Geotail encounter with reconnection diffusion region in the Earth's magnetotail: Evidence of multiple X lines collisionless reconnection?, *J. Geophys. Res.*, *109*, A05206, doi:10.1029/2003JA010031.
- Dungey, J. W. (1961), Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*, 47–48.
- Elphic, R. C., C. A. Cattell, K. Takahashi, S. J. Bame, and C. T. Russell (1986), ISEE-1 and 2 observations of magnetic flux ropes in the magnetotail: FTE's in the plasma sheet?, *Geophys. Res. Lett.*, *13*, 648–651.
- Hones, E. W., Jr. (1977), Substorm processes in the magnetotail: Comments on "On hot tenuous plasmas, fireballs, and boundary layers in the Earth's magnetotail" by L. A. Frank, K. L. Ackerson, and R. P. Lepping, *J. Geophys. Res.*, *82*, 5633–5640.
- Hughes, W. J., and D. G. Sibeck (1987), On the 3-dimensional structure of plasmoids, *Geophys. Res. Lett.*, *14*, 636–639.
- Kennel, C. F. (1995), *Convection and Substorms Paradigms of Magnetospheric Phenomenology*, Oxford Univ. Press, New York.
- Moldwin, M. B., and W. J. Hughes (1994), Observations of earthward and tailward propagating flux rope plasmoids: Expanding the plasmoid model of geomagnetic substorms, *J. Geophys. Res.*, *99*, 183–198.
- Nagai, T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T. Yamamoto, T. Mukai, A. Nishida, and S. Kokubun (1998), Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations, *J. Geophys. Res.*, *103*, 4419–4440.
- Nagai, T., I. Shinohara, M. Fujimoto, M. Hoshino, Y. Saito, S. Machida, and T. Mukai (2001), Geotail observations of the Hall current system: Evidence of magnetic reconnection in the magnetotail, *J. Geophys. Res.*, *106*, 25,929–25,949.
- Ohtani, S., M. A. Shay, and T. Mukai (2004), Temporal structure of the fast convective flow in the plasma sheet: Comparison between observations and two-fluid simulations, *J. Geophys. Res.*, *109*, A03210, doi:10.1029/2003JA010002.
- Øieroset, M., T. D. Phan, M. Fujimoto, R. P. Lin, and R. P. Lepping (2001), In situ detection of collisionless reconnection in the Earth's magnetotail, *Nature*, *412*, 414–417.
- Rème, H., et al. (2001), First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment, *Ann. Geophys.*, *19*, 1303–1354.
- 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.
- Schindler, K. (1974), A theory of the substorm mechanism, *J. Geophys. Res.*, *79*, 2803–2810.
- Schwartz, S. J. (1998), Shock and discontinuity normals, mach numbers and related parameters, in *Analysis Methods for Multi-spacecraft Data*, edited by G. Paschmann and P. W. Daly, pp. 249–270, Int. Space Sci. Inst., Bern.
- Slavin, J. A., E. I. Tanskanen, M. Hesse, C. J. Owen, M. W. Dunlop, S. Imber, E. A. Lucek, A. Balogh, and K.-H. Glassmeier (2005), Cluster observations of traveling compression regions in the near-tail, *J. Geophys. Res.*, doi:10.1029/2004JA010878, in press.
- Slavin, J. A., E. J. Smith, D. G. Sibeck, D. N. Baker, R. D. Zwickl, and S.-I. Akasofu (1985), An ISEE 3 study of average and substorm conditions in the distant magnetotail, *J. Geophys. Res.*, *90*, 10,875–10,895.
- Slavin, J. A., et al. (2002), Simultaneous observations of earthward flow bursts and plasmoid ejection during magnetospheric substorms, *J. Geophys. Res.*, *107*(A7), 1106, doi:10.1029/2000JA003501.
- Slavin, J. A., R. P. Lepping, J. Gjerloev, D. H. Fairfield, M. Hesse, C. J. Owen, M. B. Moldwin, T. Nagai, A. Ieda, and T. Mukai (2003a), Geotail observations of magnetic flux ropes in the plasma sheet, *J. Geophys. Res.*, *108*(A1), 1015, doi:10.1029/2002JA009557.
- Slavin, J. A., et al. (2003b), Cluster electric current density measurements within a magnetic flux rope in the plasma sheet, *Geophys. Res. Lett.*, *30*(7), 1362, doi:10.1029/2002GL016411.
- Ueno, G., S. Machida, T. Mukai, Y. Saito, and A. Nishida (1999), Distribution of X-type magnetic neutral lines in the magnetotail with Geotail observations, *Geophys. Res. Lett.*, *26*, 3341–3344.
- Zong, Q.-G., et al. (2004), Cluster observations of earthward flowing plasmoid in the tail, *Geophys. Res. Lett.*, *31*, L18803, doi:10.1029/2004GL020692.
- A. Balogh, S. Imber, and E. A. Lucek, The Blackett Laboratory, Imperial College London, London SW7 2BW, UK.
- I. Dandouras, Centre d'Etude Spatiale des Rayonnements/Centre National de la Recherche Scientifique—Université Paul Sabatier, F-31028 Toulouse, France.
- J. P. Eastwood, M. L. Goldstein, D. G. Sibeck, and J. A. Slavin, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (jonathan.p.eastwood@gssc.nasa.gov)
- B. Lavraud, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.
- M. Sitnov, Institute for Research in Electronic and Applied Physics, University of Maryland, College Park, MD 20742–3921, USA.