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Crater FTEs: Simulation results and THEMIS observations

D. G. Sibeck,[1] M. Kuznetsova,[1] V. Angelopoulos,[2] K.-H. Glaßmeier,[3] and J. P. McFadden[4]

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[1] The BATS-R-US magnetohydrodynamic (MHD) model predicts flux transfer events (FTEs) with strong core magnetic fields embedded within a broadened current layer of weak magnetic field strengths on the equatorial dayside magnetopause during intervals of southward and duskward interplanetary magnetic field (IMF) orientation. Multipoint THEMIS observations at 2202 UT on June 20, 2007 of a southward-moving FTE on the post-noon magnetopause confirm the predictions of the model. THEMIS-E and -A with large impact parameters simply observe enhanced magnetic field strengths in draped magnetosheath magnetic field lines, THEMIS-B and -C with moderate impact parameters pass through the broadened current layer to observe crater FTEs with deep troughs bounding a strong core field, while THEMIS-D with a very low impact parameter observes the core magnetic field strength enhancement embedded in the current layer. **Citation:** Sibeck, D. G., M. Kuznetsova, V. Angelopoulos, K.-H. Glaßmeier, and J. P. McFadden (2008), Crater FTEs: Simulation results and THEMIS observations, *Geophys. Res. Lett.*, *35*, L17S06, doi:10.1029/2008GL033568.

1. Introduction

[2] Component reconnection models predict reconnection along extended lines passing through the vicinity of the subsolar point on the dayside magnetopause. The lines tilt in response to the IMF orientation, running from southern dawn to northern dusk during periods of duskward IMF orientation [*Sonnerup*, 1974]. Reconnection along extended parallel x-lines generates flux ropes of spiraling magnetic fields [*Lee and Fu*, 1985]. When there is no guide field, core magnetic field strengths are weak [*Ding et al.*, 1991]. When there is a guide field, newly reconnected magnetic field lines sweep up magnetosheath field lines to create strong core region magnetic fields [*Scholer*, 1988].

[3] Pressure gradient and magnetic curvature forces guide the motion of the newly reconnected magnetic field lines within flux ropes. Spacecraft that remain outside passing events should observe transient enhancements in the draped magnetic field strength and bipolar magnetic field perturbations in the direction normal to the nominal magnetopause [*Farrugia et al.*, 1987]. Spacecraft that enter the events should observe characteristic bipolar magnetic field signatures, mixtures of magnetosheath and magnetospheric plasmas, and either enhancements (in the presence of guide fields) or crater-like variations (in the absence of guide fields) in the total magnetic field strength. Plasma flow perturbations ahead, behind, and within the events should be in the direction of event motion, whereas those in the ambient media on the flanks of the events should be in the direction opposite event motion [*Sibeck and Smith*, 1992].

[4] Observations in the vicinity of the dayside magnetopause during periods of southward IMF orientation confirm that FTEs with enhanced or crater-like magnetic field strength variations are common [*Russell and Elphic*, 1978; *Rijnbeek et al.*, 1987]. However, some FTEs exhibit more complicated signatures in which magnetic field strength enhancements bound trenches which in turn bound slight increases in the field at the center [*LaBelle et al.*, 1987].

[5] This paper addresses the latter type of event. It presents results from a high spatial resolution global MHD model that predicts the formation of an isolated FTE between tilted reconnection lines passing through the subsolar magnetopause. The magnetic field strength within the core of this event is far greater than that in the neighboring regions. This core region magnetic field lies embedded within the weak magnetic field strengths of the current layer. The event bulges outward into both the magnetosheath and magnetosphere. Consequently, spacecraft entering the event should observe magnetic field strength enhancements bounding trench-like magnetic field strength decreases, which in turn bound a strong core magnetic field. Multipoint THEMIS observations of an FTE on the postnoon magnetopause confirm these predictions and provide evidence for reverse flow perturbations on the flanks of the event.

2. MHD Simulation

[6] We describe predictions of the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATS-R-US) MHD model developed at the Center for Space Environment Modeling of the University of Michigan [*Powell et al.*, 1999]. BATS-R-US employs an adaptive grid composed of rectangular blocks arranged in varying degrees of spatial refinement. The grid resolution is 1/16 R_E in the vicinity of the dayside and flank magnetopause. The model derives ionospheric electric potentials and conductances from magnetospheric field-aligned currents. The Pedersen and Hall conductivities are constant at 5 and 0 mhos, respectively. The time step is <1s.

[7] We ran the model for the solar wind time series observed by ACE on May 20, 2007, namely a relatively steady duskward and southward IMF (GSM B_X, B_Y, B_Z = 0, 3, −1) nT, solar wind densities ranging from 1–2 cm^{-3}, velocities ∼550 km s^{-1}, and temperatures ∼1x10^5 K. Figure 1 shows the predictions of the model for a post-

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.
[3]Technical University, Braunschweig, Germany.
[4]Space Sciences Laboratory, University of California, Berkeley, California, USA.

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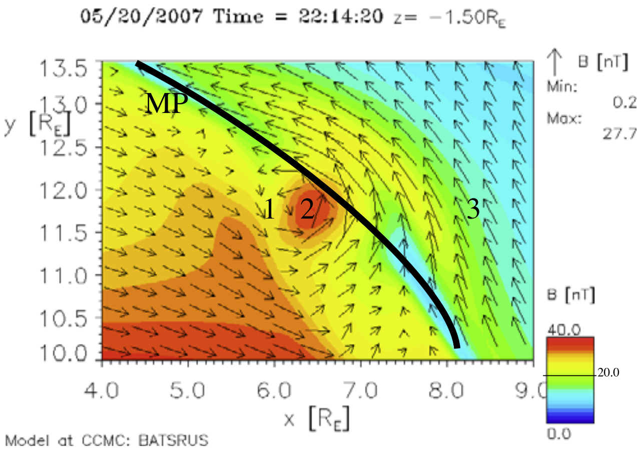

Figure 1. MHD simulation predictions for magnetic field strengths and vectors in a post-noon cut through the GSM Z = −1.5 R_E plane.

noon cut at 22:14:20 UT. The magnetopause layer of depressed (10–15 nT) magnetic field strengths separates strong (30 nT) northward, sunward, and dawnward magnetic fields in the magnetosphere on the left from southward, antisunward, and duskward magnetic fields in the magnetosheath on the right. Magnetosheath magnetic field strengths range from ∼30 nT just outside the magnetopause to 10 nT further away. An FTE whose ∼0.5 R_E wide core exhibits magnetic field strengths (∼40 nT) greater than those in either the nearby magnetosphere or magnetosheath, lies embedded within the current layer at (X, Y) = (6.4, 11.7) R_E. Magnetic field lines within the FTE spiral about an axis that runs from southern dawn to northern dusk, consistent with the component reconnection lines predicted for the observed IMF orientation. Magnetosheath magnetic field lines drape gently over the event over a broad (several R_E) region along the magnetopause.

[8] Densities and temperatures within the FTE lie between magnetosheath and magnetospheric values (not shown). Plasma flows duskward and antisunward within the FTE, but at speeds slightly greater than those in the nearby magnetosheath. By contrast, flows are strongly sunward in the magnetosphere immediately adjacent to the FTE. Only weak flows normal to the nominal magnetopause occur within and outside the FTE.

[9] Figure 2 presents magnetic field strengths and components normal to the nominal magnetopause at three points within the simulation box from 2210 to 2216 UT. Spacecraft 1 (red trace) began and ended the interval in the magnetosphere, as indicated by strong (∼26–27 nT) magnetic field strengths. It saw magnetic field strength enhancements at 2212 and 2214:20 UT. The enhancement to ∼29 nT at 2214 UT was bounded by depressed (20 nT) fields at 2212:30 and 2215 UT, resulting in a crater-like magnetic field signature. The depressions result from partial entries into the current layer, while the enhancements result from grazing encounters with strong fields at the centers of two FTEs. Spacecraft 2 (blue trace) was in the current layer from 2210 to 2211:30 UT, 2213 to 2214, and after 2215 UT. This spacecraft observed two isolated spikes in the magnetic field strength to values greater than or equal to those in either the magnetosheath or magnetosphere when entering the core regions of the 2212 and 2214:20 UT FTEs. Spacecraft 3 (dashed black trace) remained within the magnetosheath to observe only slight magnetic field strength enhancements to ∼16 nT associated with the same two FTEs. All three spacecraft observed bipolar (−, +) magnetic field signatures normal to the nominal magnetopause centered on the magnetic field strength enhancements.

3. Observations

[10] The THEMIS mission comprises 5 identical spacecraft and a dedicated array of ground magnetometers (V. Angelopoulos et al., First results from the THEMIS mission, submitted to *Space Science Review,* 2008). Magnetopause physics, and FTEs in particular, are a primary science focus of the mission (D. G. Sibeck and V. Angelopoulos, THEMIS science objectives and mission phases, submitted to *Space Science Review*, 2008). At 2202 UT on May 20, 2007, the five THEMIS spacecraft moved inbound nearly perpendicular to the post-noon magnetopause along their common equatorial orbit. As indicated by Table 1, in order of increasing distance from Earth, the spacecraft were arrayed as follows: THEMIS-B, THEMIS-C, THEMIS-D, THEMIS-E, and THEMIS-A. The difference in radial distances from Earth of THEMIS-B and -A was 0.65 R_E.

[11] Figure 3 presents THEMIS-A to -E magnetic field observations (U. Auster et al., The THEMIS fluxgate magnetometer, submitted to *Space Science Review*, 2008) in boundary normal coordinates, where **l** lies in the plane of the magnetopause and points in the direction of the magnetospheric magnetic field, **n** lies normal to the magnetopause and points outward, and m completes the triad by pointing dawnward [*Russell and Elphic*, 1978]. THEMIS-B and C (solid and dashed blue traces, respectively) observed a steady northward magnetospheric magnetic field prior to 2202 UT and after 2202:30 UT with (B_l, B_m) = (30, 0) nT, whereas THEMIS-E and A (dashed and solid black traces, respectively) observed a

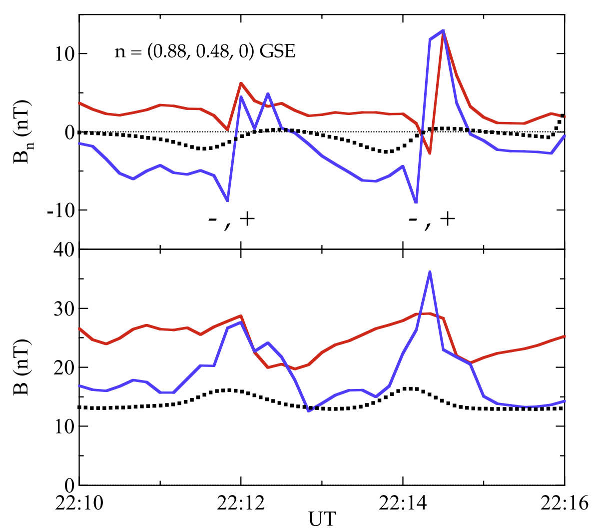

Figure 2. Predicted variations in the magnetic field component normal to the nominal magnetopause and the magnetic field strength at three points (1, 2, 3) within the MHD simulation domain of Figure 1.

Table 1. Positions of THEMIS Spacecraft at 2200 UT

Spacecraft	GSM X	GSM Y	GSM Z	R (R_E)
THEMIS-A	6.23	12.88	1.62	14.40
THEMIS-B	4.99	12.70	1.70	13.75
THEMIS-C	5.06	12.79	1.70	13.86
THEMIS-D	5.42	12.80	1.68	14.00
THEMIS-E	6.02	12.95	1.63	14.37

southward and duskward magnetosheath magnetic field during the same intervals with (B_l, B_m) = (−20, −10) nT. The large (~150°) shear angle between these ambient magnetospheric and magnetosheath magnetic fields favored magnetic reconnection. Prior to 2202 UT and between 2202:30 and 2204 UT, THEMIS-D (red trace) lay within the magnetopause current layer, where the north/south component of the magnetic field oscillated between values weaker than those in either the magnetosheath or the magnetosphere. After 2204 UT, THEMIS-D joined THEMIS-B and -C in the magnetosphere (not shown).

[12] From 2202 to 2202:30 UT, all five THEMIS spacecraft observed an FTE marked by bipolar (−, +) B_n signatures normal to the nominal magnetopause. As predicted, these signatures were most pronounced at THEMIS-D within the current layer, but were also large at THEMIS-B and -C. At THEMIS-E and -A, the initial negative pulse was weak and protracted, but the subsequent positive pulse was comparable to that seen by the other spacecraft.

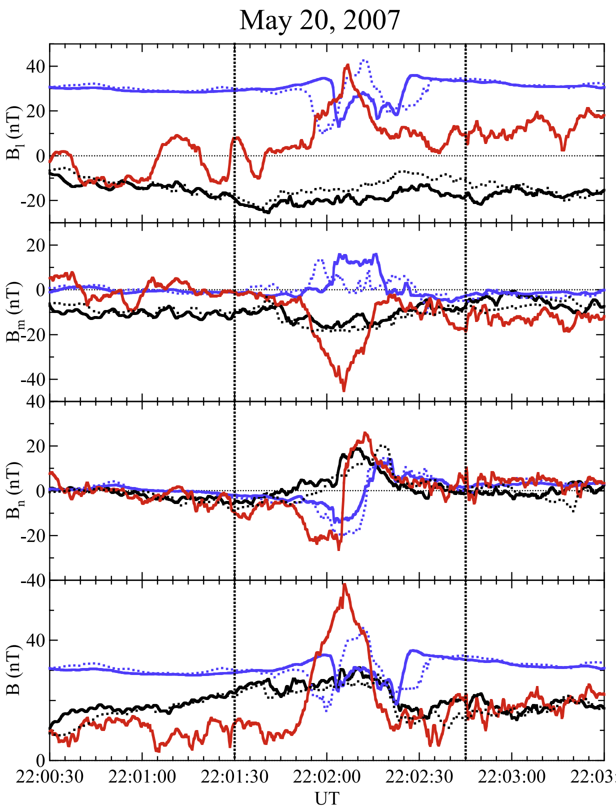

Figure 3. THEMIS-B (solid blue), -C (dashed blue), -D (red), -E (dashed black), and -A (solid black) observations of the magnetic field in boundary normal components from 2200:30 to 2203:30 UT on May 20, 2007.

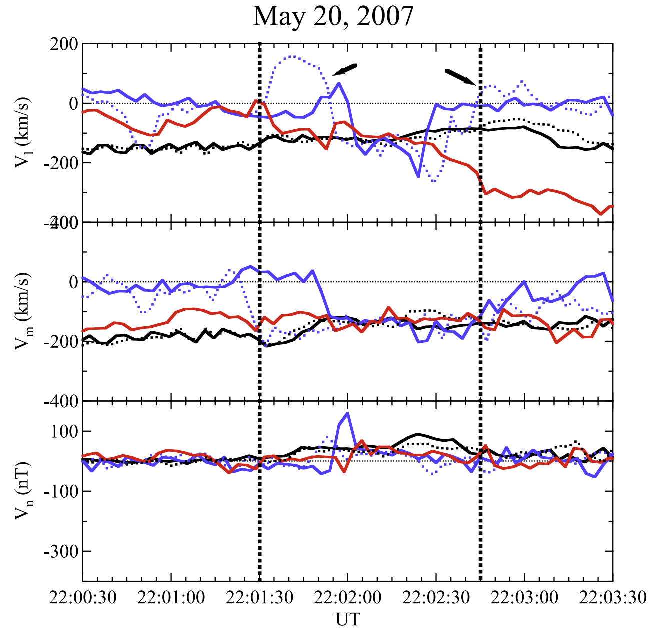

Figure 4. THEMIS-B (solid blue), -C (dashed blue), -D (red), -E (dashed black), and -A (solid black) observations of the ion velocity in boundary normal components from 2200:30 to 2203:30 UT on May 20, 2007.

[13] THEMIS-B and -C observed crater-like magnetic field strength variations in which field strength increases bounded trenches, which in turn bounded a central peak. The duration of these signatures was longer, and the central peak higher, at THEMIS-C than THEMIS-B, suggesting that THEMIS-C passed closer to the center of the event than THEMIS-B. Note that THEMIS-B and -C observed positive (dawnward) B_m deflections within the core region of the event.

[14] By contrast, THEMIS-E and -A remained in the magnetosheath throughout the event. Here they observed an enhanced negative (or duskward) Bm component. THEMIS-D, previously in the current layer, observed magnetic field strengths greater than those in either the magnetosheath or magnetosphere. Within the core region of the event, the magnetic field pointed in the (B_l, B_m) = (40, −45) nT direction. The greatly enhanced magnetic field strengths within the core region of this event are consistent with the MHD model predictions reported above, but much stronger than those seen in the events reported by *LaBelle et al.* [1987].

[15] Figure 4 presents the corresponding plasma velocities observed by the electrostatic analyzer (J. P. McFadden et al., The THEMIS ESA plasma instrument and in-flight calibration, submitted to *Space Science Review*, 2008) on THEMIS. THEMIS-E and -A remained within the magnetosheath throughout the interval, where they observed southward and duskward flows, (V_l, V_m) = (−150, −100 to −200) km s^{-1}. THEMIS-B and -C observed weak flows within the magnetosphere, but flows very similar to those in the magnetosheath while within the FTE from 2201:30 to 2202:30 UT. Black arrows in the top panel indicate times on the edges of the event when THEMIS-B and -C observed northward flows. In the current sheet, THEMIS-D observed duskward flows prior to the arrival of the FTE, flows similar

to those in magnetosheath while within the FTE, and strong southward (and duskward) flows after the FTE (from 2202:30 UT onward). With the possible exception of a brief outward flow seen by THEMIS-B at 2202 UT, none of the spacecraft observed significant flows normal to the nominal magnetopause.

4. Discussion

[16] The close correspondences between MHD model predictions and the enhanced magnetic field strengths observed by THEMIS-E and -A in the magnetosheath, the crater-like structure observed by THEMIS-B and -C in the magnetosphere, and the strong core magnetic field strengths observed by THEMIS-D in the current layer, indicate that crater-like FTEs can be interpreted as evidence for core regions of strong magnetic field strengths embedded within broadened current layers of weak magnetic field strengths.

[17] THEMIS-E and -A observed southward and duskward magnetosheath magnetic fields. Within the framework of the component reconnection model, reconnection along two or more subsolar reconnection lines should have resulted in an FTE with an axis running from southern dawn to northern dusk. At equatorial post-noon locations, the THEMIS spacecraft should have been located south of the nominal reconnection line(s) and observed southward moving events.

[18] THEMIS observations confirm these predictions. THEMIS-D observed a northward and duskward magnetic field orientation within the core region, indicating an axis running from southern dawn to northern dusk. The reverse (inward/outward) bipolar B_n signatures seen by all the spacecraft indicate southward event motion [e.g., *Rijnbeek et al.*, 1982]. Plasma observations also confirm the southward motion of the event. Upon entering the event, THEMIS-B and -C observed southward and duskward flows. The strongly northward flows in the magnetosphere that both THEMIS-B and -C observed just before entering the event and the slightly northward flows they observed upon reentering the magnetosphere provide evidence for the flows opposite event motion in the ambient media predicted on the flanks of FTEs.

[19] The magnetic field within the event was twisted about the axial field. Whereas THEMIS-B and -C observed dawnward magnetic field perturbations within the trenches on the Earthward side of the event, THEMIS-E and -A observed duskward magnetic field perturbations on the magnetosheath side of the event. While the northward and duskward pointing core magnetic field within the events observed by THEMIS-D can result from a smooth rotation from the southward and duskward magnetosheath to the northward magnetospheric magnetic field orientations within the event, it is difficult to see how it can result from interconnected magnetosheath-magnetospheric magnetic field lines 'snow-plowing' unreconnected southward and duskward magnetosheath magnetic field lines in their path.

[20] However, even a rotation between the magnetosheath and magnetospheric magnetic field orientations cannot explain the dawnward tilting magnetic field lines within the trenches on the Earthward side of the event. Although *Saunders et al.* [1984] invoked Alfvén waves to explain correlated field and flow signatures within FTEs, this event provides no evidence for the required plasma fluctuations. It seems more likely that the tilts in the magnetic field orientations seen within the trenches and magnetosheath simply result from draping over the core region. Since only the component of the magnetic field transverse to the event axis increases [*Farrugia et al.*, 1987], draped magnetic fields rotate towards directions perpendicular to that axis. In the present case, the northward magnetospheric magnetic field backs dawnward in the presence of an event with an axis running from southern dawn to northern dusk, and the strongly southward magnetosheath magnetic field backs duskward.

[21] Finally, we note that *Lui et al.* [2008] employed a reconstruction technique based on the Grad-Shafronov equation and THEMIS-D plasma and magnetic field observations to demonstrate that the core region of this same FTE has spatial dimensions $\sim$2000 km along and perpendicular to the magnetopause, a core magnetic field strength exceeding 50 nT, and an axial current density >40 nA m^{-2}.

5. Conclusion

[22] We presented THEMIS observations of a crater FTE on the afternoon magnetopause whose internal structure, including a strong core magnetic field bounded by weak troughs, agrees well with MHD model predictions. The multipoint measurements indicate that crater-like signatures result from spacecraft passages through the weak magnetic fields of a broadened current layer into the strong magnetic fields within the core of the event. For the observed duskward and southward magnetosheath magnetic field orientation, the component reconnection model predicts southward-moving events at the equatorial post-noon location of the THEMIS spacecraft. Both bipolar (inward/outward) magnetic field signatures normal to the nominal magnetopause and in situ flow perturbations indicate that the event was indeed moving southward and duskward on the magnetopause. Although the event moves with the background magnetosheath flow, the high speeds flows seen within the magnetopause current layer indicate that reconnection continued after the event's passage. Northward flows just inside the magnetosphere on the edges of the event are consistent with the reverse flows expected on the flanks of southward-moving events.

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References

Ding, D.-Q., L.-C. Lee, and Z.-W. Ma (1991), Different FTE signatures generated by the bursty single X line reconnection and the multiple X line reconnection at the dayside magnetopause, *J. Geophys. Res.*, *96*, 57–66.
Farrugia, C. J., R. C. Elphic, D. J. Southwood, and S. W. H. Cowley (1987), Field and flow perturbations outside the reconnected field line region in flux transfer events: Theory, *Planet. Space Sci.*, *35*, 227–240.
LaBelle, J., R. A. Treumann, G. Haerendel, O. H. Bauer, G. Paschmann, W. Baumjohann, H. Lühr, R. R. Anderson, H. C. Koons, and R. H. Holzworth (1987), AMPTE IRM Observations of Waves Associated with Flux Transfer Events in the Magnetosphere, *J. Geophys. Res.*, *92*, 5827–5843.

Lee, L.-C., and Z.-F. Fu (1985), A theory of magnetic flux transfer at the Earth's magnetopause, *Geophys. Res. Lett.*, *12*, 105–108.

Lui, A. T. Y., D. G. Sibeck, T. Phan, V. Angelopoulos, J. McFadden, C. Carlson, D. Larson, J. Bonnell, K.-H. Glassmeier, and S. Frey (2008), Reconstruction of a magnetic flux rope from THEMIS observations, *Geophys. Res. Lett.*, *35*, L17S05, doi:10.1029/2007GL032933.

Powell, K. G., P. L. Roe, T. J. Linde, T. I. Gombosi, and D. L. De Zeeuw (1999), A solution adaptive upwind scheme for ideal magnetohydrodynamics, *J. Comput. Phys.*, *154*, 284–309.

Rijnbeek, R. P., S. W. H. Cowley, D. J. Southwood, and C. T. Russell (1982), Observations of reverse polarity flux transfer events on the dayside magnetopause, *Nature*, *300*, 23–26.

Rijnbeek, R. P., C. J. Farrugia, D. J. Southwood, M. W. Dunlop, W. A. C. Mier-Jedrzejewicz, C. P. Chaloner, D. S. Hall, and M. F. Smith (1987), A magnetic boundary signature within flux transfer events, *Planet. Space Sci.*, *35*, 871–878.

Russell, C. T., and R. C. Elphic (1978), Initial ISEE magnetometer results: Magnetopause observations, *Space Sci. Rev.*, *22*, 681–715.

Saunders, M. A., C. T. Russell, and N. Sckopke (1984), Flux transfer events—Scale size and interior structure, *Geophys. Res. Lett.*, *11*, 131–134.

Scholer, M. (1988), Strong core magnetic fields in magnetopause flux transfer events, *Geophys. Res. Lett.*, *15*, 748–751.

Sibeck, D. G., and M. F. Smith (1992), Magnetospheric plasma flows associated with boundary waves and flux transfer events, *Geophys. Res. Lett.*, *19*, 1903–1906.

Sonnerup, B. U. O. (1974), Magnetopause reconnection rate, *J. Geophys. Res.*, *79*, 1546–1549.

V. Angelopoulos, IGPP, UCLA, Los Angeles, CA 90095, USA.

K.-H. Glaßmeier, Technical University, D-38106 Braunschweig, Germany.

J. P. McFadden, SSL, UCB, Berkeley, CA 94720, USA.

M. Kuznetsova and D. G. Sibeck, NASA/GSFC, Code 674, Greenbelt, MD 20771, USA. (david.g.sibeck@nasa.gov)