GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L17S24, doi:10.1029/2008GL034235, 2008

Highly periodic stormtime activations observed by THEMIS prior to substorm onset

L. Kepko,[1] J. Raeder,[1] V. Angelopoulos,[2] J. McFadden,[2] D. Larson,[2] H. U. Auster,[3] W. Magnes,[4] H. U. Frey,[2] C. Carlson,[2] M. Henderson,[5] S. B. Mende,[2] K. Yumoto,[6] H. J. Singer,[7] G. Parks,[2] I. Mann,[8] C. T. Russell,[9] E. Donovan,[10] and R. McPherron[9]

Received 4 April 2008; revised 18 April 2008; accepted 2 May 2008; published 11 June 2008.

[1] On March 24, 2007 THEMIS observed near the dusk flank several 10 minute quasi-periodic flow and magnetic field oscillations followed by the onset of a strong substorm (AL ~ -1000 nT). The substorm occurred during an interval of strongly southward IMF, near the start of the recovery phase of a small storm (SYM-H near -80 nT). Each magnetic oscillation was accompanied by a rapid flow variation, auroral intensification, energetic particle injection, and Pi2 pulsations. For several hours both prior to and following the substorm THEMIS observed highly periodic flow oscillations, with the same 10 minute periodicity. The average of these flow oscillations was non-zero and positive, indicating net sunward transport. We suggest that the long interval of oscillatory flow constituted a periodic convective mode of the magnetosphere, and further suggest that the quasi-periodic activations were associated with reconnection near the THEMIS location. **Citation:** Kepko, L., et al. (2008), Highly periodic stormtime activations observed by THEMIS prior to substorm onset, *Geophys. Res. Lett.*, *35*, L17S24, doi:10.1029/2008GL034235.

1. Introduction

[2] The magnetosphere exhibits quasi-periodic convection at a wide range of timescales, from tens of minutes to several hours. At the longest timescales are sawtooth events, which have characteristics of substorms, and may occur under moderately active driving approximately every 2–3 hours [*Henderson et al.*, 2005]. Substorms that exhibit a full loading and unloading cycle commonly occur repetitively every few hours. At short timescales, Poleward Boundary Intensifications (PBIs) have been observed to repeat with a quasi-periodic rate of once every 10–30 minutes [*Sutcliffe and Lyons*, 2002; *Lyons et al.*, 2002; *Zesta et al.*, 2006].

[3] There are still open questions of how and under what conditions the magnetosphere enters into the different modes of convective transport. The five identically instrumented spacecraft of the THEMIS mission are well suited to answer these questions [*Angelopoulos*, 2008]. On March 24, 2007, the spacecraft were located near the dusk flank and observed between 0900 and 0945 UT a series of periodic flow reversals and magnetic field oscillations with a 10-minute cadence. Each oscillation was associated with an auroral intensification, Pi2 pulsations, and a geosynchronous particle injection. Although each oscillation and associated brief interval of substorm-like phenomena could be termed a pseudo-breakup [e.g., *Rostoker*, 1998], we prefer the neutral term activation. The periodic activations culminated with the onset of a large substorm near 0945 UT. In addition to the brief interval of activations, for several hours before and after the event THEMIS observed highly periodic flow oscillations, also with a periodicity of 10 minutes. These oscillations were not associated with impulsive activity, and appear to have a source downtail from THEMIS. The flow oscillations and periodic activations occurred during an interval of strong solar wind driving, and we suggest that the magnetosphere entered a state of periodic sloshing. Net transport was sunward, but occurred in a quasi-periodic manner at different locations in the magnetosphere. We suggest that the activations were generated by magnetic reconnection near the THEMIS location, and that the periodicity of the local activations was established by periodic perturbations with a source in the nightside plasmasheet.

2. Observations

[4] The THEMIS spacecraft were launched February 16, 2007 into the pre-midnight sector with a string of pearls configuration. For this study we examine data from the fluxgate magnetometer [*Auster et al.*, 2007, 2008] and the plasma analyzer [*McFadden et al.*, 2008]. Plasma data were available in 3 forms: full distribution functions at 384 s, omnidirectional spectra at 3 s, and onboard calculated plasma moments at 3 s. Unfortunately, a table loading error caused the THEMIS on-board moments to be incorrectly calculated for the first few months of the mission (D. Larson, private communication, 2008). These 3 s moments can be partially recovered through a comparison with ground calculated moments determined from the full distributions. A linear fit between onboard moments and ground moments

[1] Space Science Center, University of New Hampshire, Durham, New Hampshire, USA.
[2] Space Sciences Laboratory, University of California, Berkeley, California, USA.
[3] Institute of Geophysics and Extraterrestrial Physics, Technical University of Braunschweig, Braunschweig, Germany.
[4] Space Research Institute of the Austrian Academy of Science, Graz, Austria.
[5] Space Science and Applications Group, Los Alamos National Laboratory, Los Alamos, New Mexico, USA.
[6] Space Environment Research Center, Kyushu University, Fukuoka, Japan.
[7] Space Weather Prediction Center, NOAA, Boulder, Colorado, USA.
[8] Department of Physics, University of Alberta, Edmonton, Alberta, Canada.
[9] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.
[10] Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada.

0094-8276/08/2008GL034235$05.00

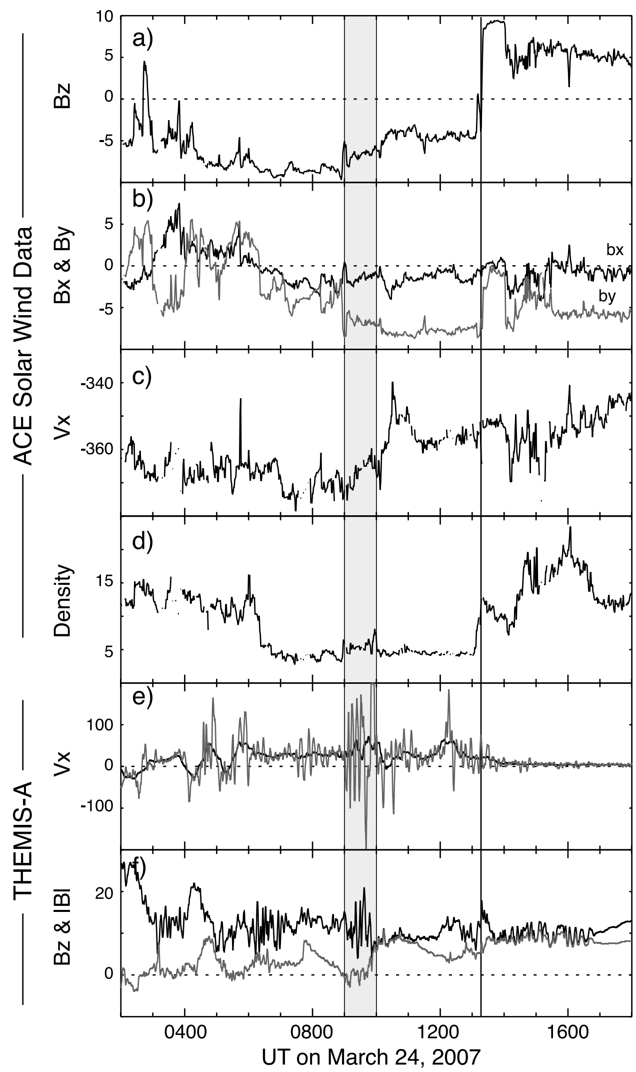

Figure 1. Solar wind data from the ACE spacecraft, propagated to the dayside magnetopause: (a) B_z, (b) B_x and B_y, (c) V_x and d) proton number density. (e) The x component of the 3-s velocity measured by THEMIS-A, with a 1-minute running average. The black line is a 30-minute running average. (f) THEMIS-A B_z and $|B|$.

determines fitting parameters that can correctly rescale the onboard X and Z components of the 3-s velocity moments with a high degree of fidelity.

[5] Solar wind data propagated to the dayside magnetopause are shown in Figures 1a–1d. IMF B_z (Figure 1a) was negative for the majority of the day and was relatively steady at $B_z \sim -8$ nT for several hours prior to 0900 UT. During the interval 0500 to 0900 UT AL (not shown) remained near -500 nT, indicating strong convection. Figure 1e shows the X component of the velocity measured by THEMIS-A, which was located near the equatorial dusk flank near $(X,Y) = (-4.5, 13.5)$ R_E GSE. Between 6 and 14 UT V_x oscillated with a period of $\sim$10 minutes. The 30-minute average (black line in Figure 1e) shows that sunward transport was non-zero during this interval, near 30 km/s. THEMIS-A B_z GSE and $|B|$ are shown in Figure 1f. Dipolarizations occurred just prior to 0800, 1000 and 1300 UT. Note that V_x continued to oscillate through the first two dipolarizations. Near 1320 UT IMF B_z turned northward, and both the flow oscillations and net sunward transport ceased soon thereafter.

[6] At 0900 UT the THEMIS probes were located near the equatorial dusk flank, with C near (−5.7, 12.8), A, B and D near (−4.5, 13.5), and E near (−3.3, 13.5) R_E GSE. The LANL-97A spacecraft was near the same local time (19 LT). Between 0900 and 1000 UT THEMIS observed a series of large amplitude velocity and magnetic field oscillations (Figures 2b and 2c). Data from other THEMIS spacecraft show qualitatively the same features (Figure 2e). Ground stations near the same local time observed Pi2 packets at 0908, 0918, 0928, and 0938 UT (Figure 2a). Each Pi2 was associated with nearly dispersionless geosynchronous particle injections at 19 LT (Figures 2f and 2g). An electron injection so near dusk is rarely observed, and implies that activity was centered near the local time of LANL-97A. The LANL-02A (14 LT) energetic proton data (Figure 2h) indicate a series of drift echoes near local noon, strong evidence that the flux increases observed by LANL-97A were injections and not simply boundary oscillations.

[7] The THEMIS all-sky imager (ASI) stations in Alaska, near 19 LT, captured auroral activity associated with each of the activations. The imagers observed multiple arcs drifting equatorward with a brightening approximately every 10 minutes, although the arcs did not fully break up until after 0940 UT. Snapshots bracketing the Pi2 onsets are shown in Figure 3. The first brightening was observed near 0901:06 in the southwest FOV of Kiana (KIAN, middle of the west coast of Alaska). The arc quickly dissipated and was no longer visible by 0902:18. While no Pi2 were observed at this time, THEMIS observed the start of flow and field variations. The next brightening occurred near 0909:21 UT, again along the southern edge of the KIAN FOV. The arc similarly dissipated in a few minutes. The third brightening occurred around 0918 UT, and appeared in both the KIAN and McGrath (MCGR, southwestern Alaska) FOVs. By 0923 UT the arc had dimmed and a new arc had formed and started to move equatorward. Near 0928 UT over MCGR a small swirl developed on a preexisting arc and quickly moved westward. The arcs continued to brighten slowly for the next 10 minutes until a large auroral breakup and substorm near 0938 UT. This breakup started eastward of Gakona (GAKO, southeastern Alaska) and then spread into MCGR and then northward. The magnetic field at the THEMIS location reconfigured at this time, consistent with expectations of a magnetospheric substorm.

3. Discussion and conclusions

[8] THEMIS observed two types of periodic activity during the interval discussed here. Between 0600 and 1400 UT THEMIS observed a persistent 10-min oscillation in the flow velocity, with a non-zero, net sunward average. Between 0900 and 0945 UT a series of periodic 10-min activations occurred, closely associated with a brief, but significant, decrease in IMF B_z (Figure 1a). Each Pi2, particle injection and auroral brightening was a manifestation of short-lived, impulsive magnetospheric activity. Only the last activation near 0938 UT exhibited the magnetic field

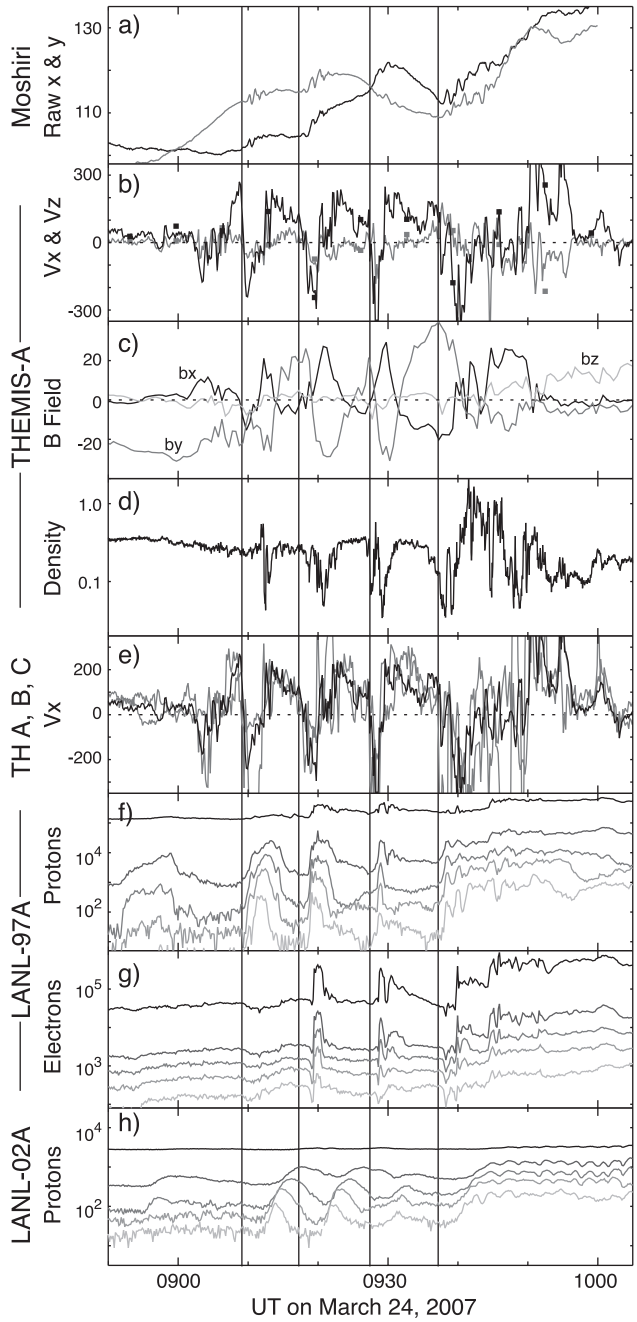

Figure 2. (a) Raw X and Y component ground magnetic field data from Moshiri, Japan, (b) the 3-s THEMIS-A V_x (black) and V_z with a 3-pt running average, (c) the three components of the magnetic field and (d) the number density. Solid rectangles in Figure 2b indicate moments calculated on the ground from full distributions. Also shown are (e) V_x from THEMIS-A, B and C and particle measurements from (f and g) LANL-97A and (h) LANL-02A.

reconfiguration, large-scale auroral expansion and strong geosynchronous particle injection consistent with substorm expansion. Despite the unusual local time (19 LT), several hours away from the nominal location of such activity, the activations exhibited characteristics similar to those observed on the nightside. Although the exact details of substorm onset are still subject to debate, nightside substorm activity is well understood to be related to unloading of tail plasma through magnetic reconnection. The combined THEMIS observations of strong thinning, dipolarization, and fast flows at the flank, along with geosynchronous dispersionless injections and auroral activations, are qualitatively similar to nightside substorm activity, and suggests that one or more reconnection sites existed near the meridian of 19 LT.

[9] While it is rare to observe such strong substorm activity very near the dusk flank [see, e.g., *Gelpi et al.*, 1987], it can be understood as a consequence of the IMF conditions. The 12-hour interval prior to 1300 UT occurred under heavy solar wind driving, and is characterized by AL as an SMC or by SYM-H as a small storm. During an SMC, reconnection occurs close to the Earth to facilitate rapid convection [*Sergeev et al.*, 1996]. In addition, for several hours prior to the event both IMF B_y and B_z were negative. Under this orientation reconnection at the dayside magnetopause occurs preferentially pre-noon in the northern hemisphere and post-noon in the southern [*Crooker*, 1979; *Luhmann et al.*, 1984]. This asymmetric flux loading twists the geomagnetic tail such that the plane of the plasmasheet is rotated clockwise viewed from Earth. This is evident in the THEMIS magnetic field data (Figure 2c). Prior to the substorm, the magnetic field at the location of THEMIS was dominated by negative B_y, which placed the spacecraft above the current sheet. After the substorm the spacecraft were located in the central plasmasheet, an indication that the substorm lead to an untwisting of the dusk plasmasheet. During current sheet crossings, B_z was near zero until after the substorm near 0945. This untwisting of the plasmasheet and topological reconfiguration of the magnetic field is further evidence for magnetic reconnection near the dusk flank.

[10] During the activations the magnetic field oscillations in Figure 2 propagated towards the dayside with a speed of a few 100 km/s [*Gabrielse et al.*, 2008]. We note that the oscillations continued through the dipolarizations at 0800 and 1000 UT, consistent with a non-local source. Later in the day THEMIS observed magnetic field oscillations for several hours after the convective flow had ceased and the IMF had turned northward (Figure 4). Timing obtained from cross-correlation analysis is consistent with propagation away from midnight, towards the flanks, at a speed of $\sim$40 km/s. This suggests that the periodicity was established somewhere in the nightside plasmasheet, near the midnight meridian. We suggest that the periodicity of the activations was not established locally. Rather, periodic perturbations propagating from the nightside likely modulated local dusk dynamics.

[11] The source of the 10-minute periodicity is unclear. Kelvin-Helmholtz seems unlikely on the basis that the perturbations appeared to propagate away from midnight. The solar wind number density increased slightly during the interval, and contained periodicities similar to those observed by THEMIS (Figure 1d). While several papers have argued for the existence of periodic solar wind number density variations [e.g., *Kepko et al.*, 2002], in this case there is little evidence of number density oscillations prior to or after the event to sustain such a conclusion here. Still,

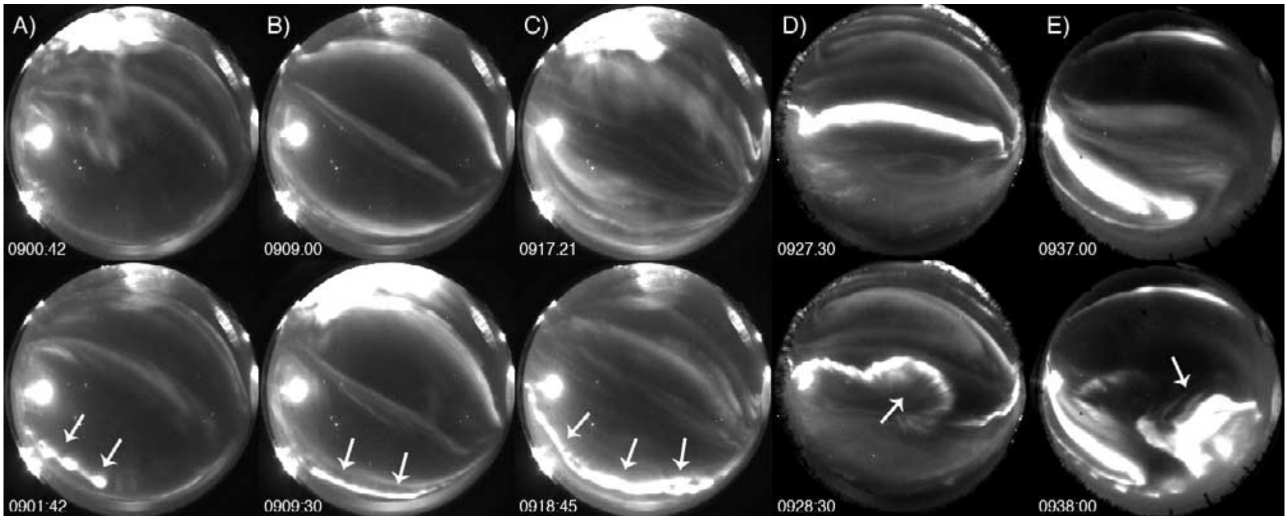

Figure 3. All sky imager data bracketing the times of Pi2 onsets from THEMIS ground stations. Field-of-view is (a–c) Kiana, Alaska, (d) McGrath, Alaska, and (e) Gakona, Alaska. Arrows mark the locations of activations.

without measurements in the immediate upstream solar wind, we cannot rule out completely this possibility.

[12] We have examined magnetometer data from a variety of ground stations, but have not found sustained signatures of a 10 min periodicity. Magnetometers near the same local time of THEMIS measured currents associated with the multiple arcs, but no clear signature of a 10 min periodicity. Magnetograms from the IMAGE chain showed 10-minute oscillations between 0500 and 0600 UT, when IMAGE was located near dawn. There is little evidence in other ground magnetometers of similar periodicities. The lack of a persistent ionospheric signature suggests that the source of the periodicity is either highly localized or else decoupled from the ionosphere. The ASI observations of temporally stable arcs argues for the existence of magnetospheric flow shears and ionospheric electric potentials which could decouple any magnetospheric oscillations from the magnetosphere.

[13] Periodicities were intermittently observed at geosynchronous orbit by several spacecraft. Between 0600 and 0900 UT variations in the electron flux at the 10-minute timescale were observed by LANL-89, near 2130 LT. Periodic injections quite similar to those observed by LANL-97A were measured by LANL-94 between 0600 and 0700 UT near 2030 LT. Spacecraft located on the dayside did not observe this periodic activity. We are unable to ascertain if the observations represent a local time effect or a radial dependance of activity. A combination of both is likely. Geotail was located in the midtail plasmasheet near $(-18, -1)\ R_E$. Geotail observed short intervals of 10-minute oscillations, most clearly between 0545 and 0630 UT in B_x. But, as with the geosynchronous and ground data, the oscillations were intermittent.

[14] The apparent discrepancy between the THEMIS observations of semi-continuous oscillations and the lack of consistent signature in other magnetospheric locations is likely explained by the location of THEMIS. The flank magnetosphere acts as a funnel of nightside convection, and activity that occurs on the nightside must eventually pass through the flank to reach the dayside. The non-zero average of V_x for several hours indicates net sunward transport, and suggests that the oscillations represent a periodic sloshing of the magnetosphere. The observations further indicate that this periodic convection was sporadic and localized to the pre-midnight sector. For the interval 0900–0945 UT, substorm activity occurred near the local time of THEMIS and LANL-97A, near the 19 LT meridian. The strong flows, dipolarization and particle injections are consistent with loading of magnetic flux near the dusk flank and unloading through a substorm and magnetic reconnection. The periodicity of the duskside activations was likely determined by sunward propagating impulses from further downtail.

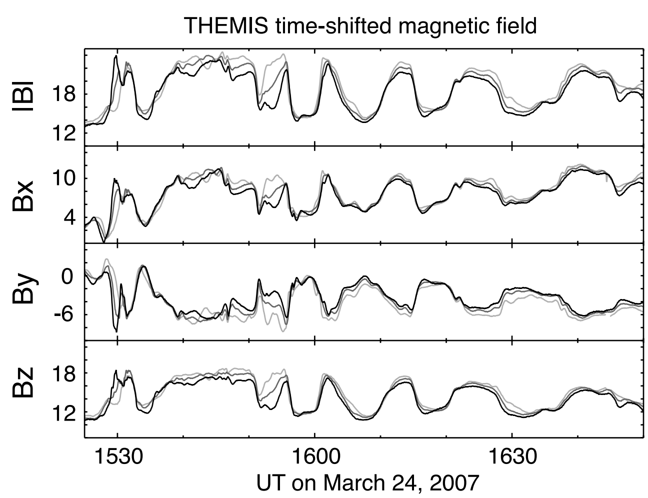

Figure 4. Magnetic field data from THEMIS D, B and A. The spacecraft were near $(-6.6, 10.5)\ R_E$ at 1600 UT, separated by $\sim 0.4\ R_E$ in the y direction. Probe D was located closest to midnight, Probe A furthest. Data from probes B and A have been time-shifted based on cross-correlation analysis by -24 s (R = 0.96) and -60 s (R = 0.85) respectively.

[15] **Acknowledgments.** We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission. Financial support of the FGM Lead Investigator Team at the Technical University of Braunschweig by the German Ministerium für Wirtschaft und Technologie and the Deutsches Zentrum für Luft- und Raumfahrt under grant 50QP0402 is acknowledged. We acknowledge J. H. King, N. Papatashvilli and CDAWeb for the solar wind data.

References

Angelopoulos, V. (2008), The THEMIS mission, *Space Sci. Rev.*, in press.
Auster, H. U., et al. (2007), ROMAP: Rosetta Magnetometer and Plasma Monitor, *Space Sci. Rev.*, *128*, 221, doi:10.1007/s11214-006-9033-x.
Auster, H. U., et al. (2008), The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, in press.
Crooker, N. U. (1979), Dayside merging and cusp geometry, *J. Geophys. Res.*, *84*, 951.
Gabrielse, C., V. Angelopoulos, A. Runov, L. Kepko, K.-H. Glassmeier, U. Auster, J. McFadden, C. Carlson, and D. Larson (2008), Propagation characteristics of plasma sheet oscillations during a small storm, *Geophys. Res. Lett.*, doi:10.1029/2008GL033664, in press.
Gelpi, C., H. J. Singer, and W. J. Hughes (1987), A comparison of magnetic signatures and DMSP auroral images at substorm onset: Three case studies, *J. Geophys. Res.*, *92*, 2447.
Henderson, M. G., G. D. Reeves, R. Skoug, M. F. Thomsen, M. H. Denton, S. B. Mende, T. J. Immel, P. C. Brandt, and H. J. Singer (2005), Magnetospheric and auroral activity during the 18 April 2002 sawtooth event, *J. Geophys. Res.*, *111*, A01S90, doi:10.1029/2005JA011111.
Kepko, L., H. E. Spence, and H. J. Singer (2002), ULF waves in the solar wind as direct drivers of magnetospheric pulsations, *Geophys. Res. Lett.*, *29*(8), 1197, doi:10.1029/2001GL014405.
Luhmann, J. G., R. J. Walker, C. T. Russell, N. U. Crooker, J. R. Spreiter, and S. S. Stahara (1984), Patterns of potential magnetic field merging sites on the dayside magnetopause, *J. Geophys. Res.*, *89*, 1739.
Lyons, L. R., E. Zesta, Y. Xu, E. R. Snchez, J. C. Samson, G. D. Reeves, J. M. Ruohoniemi, and J. B. Sigwarth (2002), Auroral poleward boundary intensifications and tail bursty flows: A manifestation of a large-scale ULF oscillation?, *J. Geophys. Res.*, *107*(A11), 1352, doi:10.1029/2001JA000242.
McFadden, J. P., C. W. Carlson, D. Larson, V. Angelopolos, M. Ludlam, R. Abiad, and B. Elliot (2008), The THEMIS ESA plasma instrument and in-flight calibration, *Space Sci. Rev.*, in press.
Rostoker, G. (1998), On the place of the pseudo-breakup in a magnetospheric substorm, *J. Geophys. Res.*, *25*, 217.
Sergeev, V. A., R. J. Pellinen, and T. I. Pulkkinen (1996), Steady magnetospheric convection: A review of recent results, *Space Sci. Rev.*, *75*, 551.
Sutcliffe, P. R., and L. R. Lyons (2002), Association between quiet-time Pi2 pulsations, poleward boundary intensifications, and plasma sheet particle fluxes, *Geophys. Res. Lett.*, *29*(9), 1293, doi:10.1029/2001GL014430.
Zesta, E., L. Lyons, P. C.-Wang, E. Donovan, H. Frey, and T. Nagai (2006), Auroral poleward boundary intensifications (PBIs): Their two-dimensional structure and associated dynamics in the plasma sheet, *J. Geophys. Res.*, *111*, A05201, doi:10.1029/2004JA010640.

V. Angelopoulos, C. Carlson, H. U. Frey, D. Larson, J. McFadden, S. B. Mende, and G. Parks, Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA.

H. U. Auster, Institute of Geophysics and Extraterrestrial Physics, Technical University of Braunschweig, D-38106, Braunschweig, Germany.

E. Donovan, Department of Physics and Astronomy, University of Calgary, Calgary, AB T2N 1N4, Canada.

M. Henderson, Space Science and Applications Group, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

L. Kepko and J. Raeder, Space Science Center, University of New Hampshire, Morse Hall, 39 College Road, Durham, NH 03842, USA. (larry.kepko@unh.edu)

W. Magnes, Space Research Institute of the Austrian Academy of Science, A-8042, Graz, Austria.

I. Mann, Department of Physics, University of Alberta, Edmonton, AB T6G 2J1, Canada.

R. McPherron and C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA.

H. J. Singer, Space Weather Prediction Center, NOAA, Boulder, CO 80303, USA.

K. Yumoto, Space Environment Research Center, Kyushu University, Hakozaki, Fukuoka, 812-8581, Japan.