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Simultaneous THEMIS in situ and auroral observations of a small substorm

E. Donovan,[1] W. Liu,[2] J. Liang,[2] E. Spanswick,[1] I. Voronkov,[3] M. Connors,[3] M. Syrjäsuo,[4] G. Baker,[1] B. Jackel,[1] T. Trondsen,[1] M. Greffen,[1] V. Angelopoulos,[5] C. T. Russell,[5] S. B. Mende,[6] H. U. Frey,[6] A. Keiling,[6] C. W. Carlson,[6] J. P. McFadden,[6] K.-H. Glassmeier,[7] U. Auster,[7] K. Hayashi,[8] K. Sakaguchi,[9] K. Shiokawa,[9] J. A. Wild,[10] and I. J. Rae[11]

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[1] We present ground-based and in situ observations from March 13, 2007. The THEMIS satellites were in the evening sector conjugate to THEMIS ground-based imagers. At ~0507 UT there was an optical onset on inner CPS field lines. This involved near-simultaneous brightening of 1 MLT hour longitudinal segment of the onset arc. The part of the arc that brightened was that closest to the equatorward boundary of the diffuse (proton) aurora. Within one minute, a dipolarization front moved across four THEMIS satellites. Based on their locations, the order in which they detected the dipolarization front, and the auroral evolution, we assert that the expansion phase began earthward of the four satellites and evolved radially outwards. We conclude that this onset occurred in an azimuthally localized region of highly stretched field lines.
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1. Introduction

[2] In the ionosphere, onset begins with the brightening of a preexisting or recently formed (most equatorward) auroral arc [*Akasofu*, 1964; *Lyons et al.*, 2002]. Topside ionospheric particle observations show that this arc is on closed field lines, within or poleward of the Central Plasma Sheet (CPS) proton precipitation which marks in the ionosphere the transition between dipole- and tail-like topologies [*Lui and Burrows*, 1978]. The arc brightening signals expansion phase in the inner (around the dipolar/tail-like transition) CPS, and is related to dispersionless injection, dipolarization, and the current wedge. The current wedge and dipolarization indicate a decrease in transverse current in the inner CPS due to a kinetic- or macroscale instability such as ballooning, or braking of fast CPS flows [*Roux et al.*, 1991; *Lui*, 1996; *Shiokawa et al.*, 1998; *Angelopoulos et al.*, 1999]. In many cases, inner CPS onset and auroral onset either precede or follow Near-Earth Reconnection (NER) [*Baker et al.*, 1996]. Proposed modes of CD/NER interaction are a tailward propagating rarefaction wave (CD leads to NER), or a fast flow (NER leads to CD). These two scenarios are the CD and Near Earth Neutral Line (NENL) models, respectively [*Lui*, 1996; *Baker et al.*, 1996], two paradigms within which substorm data is often interpreted.

[3] We are at an impasse as to which scenario best represents specific events. THEMIS [*Angelopoulos et al.*, 2008] blends ground-based and magnetically conjugate *in situ* observations designed to resolve the CD versus NENL controversy. *Liang et al.* [2008] present THEMIS All-Sky Imager (ASI) array [*Donovan et al.*, 2006; *Mende et al.*, 2008] observations of the onset auroral brightening for eight events. In each, the initial brightening is along a longitudinally extended region (10–20°), exhibits linear exponential growth (τ = 10–30 s), and periodic structuring along the arc (m > 100). One of those events occurred after the launch of the THEMIS satellites, at a time when the constellation was conjugate to the ASI array. The ASI data and the satellite-ground magnetic conjugacy were excellent, and the Fluxgate Magnetometers (FGM) [*Auster et al.*, 2008] were operating on each satellite. Here we present a more thorough investigation of this event to explore the relationship between the optical onset and the underlying magnetotail dynamics.

2. Observations

[4] The event occurred on March 13, 2007. Cluster observed high (~650 km/sec) solar wind speed and variable IMF direction upstream of the bow shock. There was clear weather over six ASIs spanning six hours of MLT around the satellite footprints. The activity included several auroral onsets, one at ~0507 UT that had optical onset clearly within the ASI fields of view. THEMIS E (TH-E in Figure 1) was located at ~10.5 Re radial distance and above (north of) the neutral

[1]Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada.
[2]Space Sciences Division, Canadian Space Agency, Saint-Hubert, Quebec, Canada.
[3]Athabasca University Geophysical Observatory, Athabasca University, Athabasca, Alberta, Canada.
[4]Finnish Meteorological Institute, Helsinki, Finland.
[5]IGPP, UCLA, Los Angeles, California, USA.
[6]Space Sciences Laboratory, University of California, Berkeley, Berkeley, California, USA.
[7]Instiute of Geophysics and Extraterrestrial Physics, Technical University of Braunschweig, Braunschweig, Germany.
[8]Department of Earth and Planetary Physics, University of Tokyo, Tokyo, Japan.
[9]Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan.
[10]Department of Communication Systems, Lancaster University, Lancaster, UK.
[11]Department of Physics, University of Alberta, Edmonton, Alberta, Canada.

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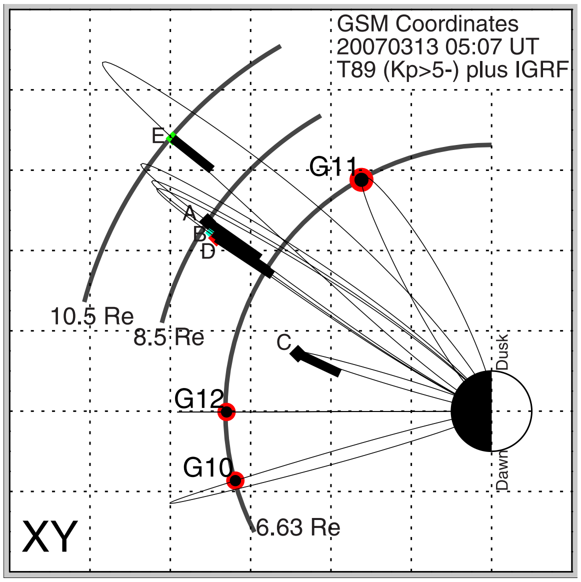

Figure 1. THEMIS and GOES locations at the first onset. THEMIS A, B, D, and E are above the neutral sheet. The field lines are from the *Tsyganenko* [1989] "T89" model. The thick black lines at each THEMIS satellite indicate the magnetic field from FGM.

sheet. TH-A,B,D were clustered around 8.5 Re, and also above the neutral sheet. TH-C was too close to Earth to be relevant. There were three GOES satellites spanning the THEMIS MLT region.

[5] Figure 2 includes three ASI mosaics (Mosaics A–C) from the 0507 UT auroral onset. Mosaic A shows the aurora ~1 minute after the onset. The arc that brightened is clearly visible across five hours of MLT (the magnetic longitude lines are one hour apart). Mosaics B and C show the aurora one and two minutes later, illustrating brightening along an azimuthally extended region with periodic structuring (m ~ 120) as discussed by *Liang et al.* [2008]. In the preceding minutes, we see no evidence of structured aurora immediately poleward of the onset arc that would indicate fast flows connecting the inner CPS with the mid-tail region (e.g., north-south structures as discussed by *Zesta et al.* [2000]) although the poleward arcs that are on the northern edge of the mosaic are active during the minutes before and after onset.

[6] Figure 2, top right panel, is the same mosaic as in Mosaic A, with context. We show the T89 Kp = 5 satellite foot points (the short curve through each symbol indicates the Kp = 3 to >5 foot points gives an idea of latitudinal mapping uncertainty). Longitudinal displacement of the foot points of an hour or more towards midnight can be expected due to field-aligned current effects [*Donovan*, 1993]. We indicate the arc that brightened with the poleward red/black curve. The NORSTAR Meridian Scanning Photometer (MSP) at Pinawa obtained scans of 486 nm "H-beta" proton and 630 nm Oxygen "redline" aurora. We have superposed meridian scans of the emissions (H-beta in blue; redline in red) assuming emission heights of 150 and 230 km, respectively. From the redline data, it is clear that closed field lines extend at least 5° latitude poleward of the onset arc [see *Blanchard et al.*, 1995]. The H-beta equatorward boundary is the ionospheric projection of the earthward limit of strong pitch angle scattering of the CPS protons responsible for the proton aurora, and hence is a proxy for the transition between tail-like and dipole-like field line topologies [see *Samson et al.*, 1992]. In the Pinawa meridian, the bright proton aurora is coincident with the band of diffuse aurora visible in the white light data.

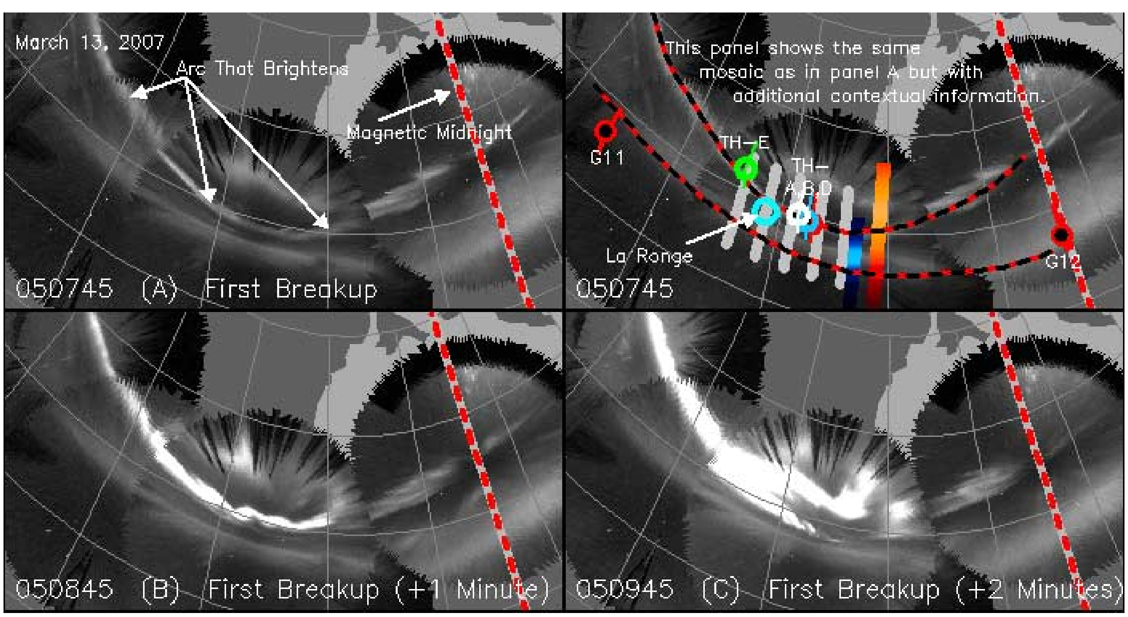

Figure 2. Three mosaics (A, B, and C) showing THEMIS ASI data from the three minutes after the optical onset. The context information overplotted on the top right panel (same as Mosaic A) is described in the text. The thick grey lines (top right panel) show the meridian slices from which the keogram in Figure 4 was obtained.

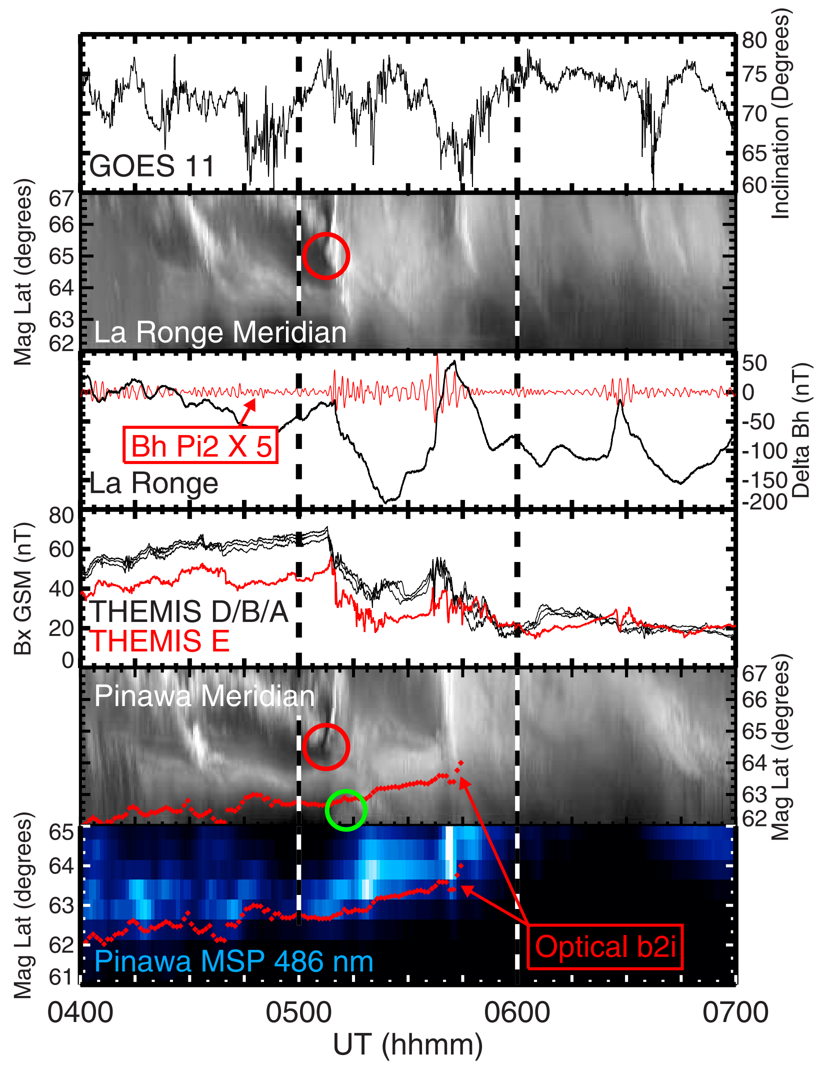

Figure 3. Overview of active period, described in detail in the text.

Assuming this relation holds at other longitudes, we use the mosaic to provide an "iso-contour" of the H-beta equatorward boundary, indicated here by the lower latitude red/black curve. Finally, we also show La Ronge, which we estimate to be the closest ground magnetometer to the onset location. The five grey strips indicate where data was extracted for keograms and line plots in Figure 4. They span one hour of MLT, and cover from 62° to 67° magnetic latitude. The onset began on or near a preexisting arc structure just poleward of the bright proton aurora, and expanded poleward. The subsequent evolution of the aurora did not result in north-south structures, and stalled before it reached the poleward limit of closed field lines (as inferred from the MSP redline data).

[7] Figure 3 is a stack plot of data from selected satellite and ground-based instruments. The two keograms show ASI data on the Pinawa and La Ronge meridians. The 0507 onset is indicated by the two red circles. THEMIS FGM Bx and the magnetic inclination at GOES 11 show dipolarization and TH-A ElectroStatic Analyzer (plasma distribution for <30 keV ions and electrons) (J. P. McFadden et al., THEMIS ESA first science results and performance issues, submitted to *Space Science Review*, 2008) data (not shown) shows CPS thickening associated with the onset (the ESA data shows TH-A to be in the CPS or PSBL at the time of onset). The La Ronge magnetometer shows a clear Pi2 burst and negative H-bay with the onset. The Pinawa H-beta keogram shows fading as discussed by *Liu et al.* [2007] in the 15 minutes prior to the first event. The red curve superposed on the bottom two plots of Figure 3 shows the "optical b2I", a proxy for the equatorward boundary of the proton aurora (see *Donovan et al.* [2003]). As well, in the minutes after the onset there is intrusion of electron aurora equatorward of the proton aurora indicating electron injection (indicated by the green circle).

[8] Figure 4 focuses on the minutes around the onset. Figure 4 (top) shows Bx from TH-A,B,D, and E. The decrease in Bx corresponds to a local decrease in cross-tail current. This dipolarization front passes TH-D at ∼050750 UT, and then B, A, and finally E at ∼050755, ∼050815, and ∼050900 UT, respectively. The satellites are aligned roughly radially (Figure 1), but in the evening sector so this indicates outward radial and/or duskward azimuthal expansion. The keogram is from the middle meridian (grey) slice in Figure 1. The preexisting arc turns off around the time of onset. Examination of the auroral data for the ten minutes

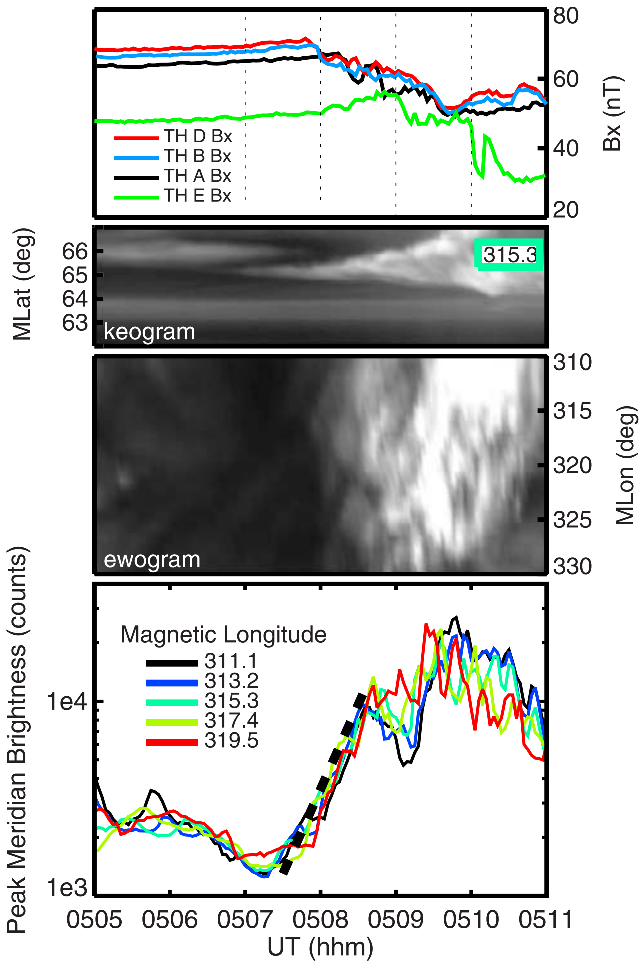

Figure 4. (first panel) GSM X-component magnetic field from FGM on THEMIS A, B, D, and E. (second panel) The keogram shows data from the middle of the meridian slices indicated by the thick grey lines in Figure 1. The diffuse aurora which we assert marks the bright proton aurora (note we are not attributing this brightness to the proton aurora) is visible in the bottom half of the keogram. (third panel) The ewogram shows the peak brightness between 62° and 67° magnetic latitude (again corresponding to the grey strips in Figure 1) as function of magnetic longitude and UT. The ewogram data is from the ASI at The Pas. (fourth panel) Peak brightness on the 5 meridian slices indicated in Figure 1. The thick dashed curve corresponds to linear growth with an e-folding time of 30 seconds.

previous to the onset indicates this turning off is not part of a cycle of a ULF wave. Further, the structure that does brighten appears as a new feature immediately equatorward of the preexisting arc as reported by *Lyons et al.* [2002]. This new feature emerges smoothly from the background, making it difficult to identify an exact optical onset time. The ewogram (east-west "gram") shows peak intensity between 62° and 67° magnetic latitude as a function of magnetic longitude and UT. It is difficult to identify an onset meridian: based on the ewogram, the brightening occurs within 20 seconds along a ~1 hour MLT region of the arc, as discussed for this and seven other events by *Liang et al.* [2008]. Nevertheless, our best estimate is that the brightening began first in the vicinity of 310 degrees magnetic longitude (La Ronge meridian).

[9] The line plots (fourth panel of Figure 4) show peak brightness along the grey meridional strips in Figure 1. The brightness along each fades to a minimum, corresponding to the turning off of the preexisting arc, and then grows linearly for ~1.5 minutes. The thick dashed curve corresponds to linear growth time (τ) of 30 seconds. The brightness on all three meridians saturates after 3τ. The brightness increases more or less uniformly across the hour of MLT west of the Pinawa meridian (within ~20 seconds).

[10] The data presented here show the following: 1) The ~0507 UT optical onset occurred immediately equatorward of a preexisting arc that spanned >5 MLT hours; 2) That preexisting arc was closest in latitude to the equatorward boundary of the proton aurora over ~1 MLT hour and the optical onset was in that 1 hour of MLT; 3) There was proton auroral fading in the 15 minutes prior to the onset; 4) The onset arc, which appeared as a new feature displaced slightly equatorward of the preexisting arc, brightened nearly simultaneously across that one hour of MLT and grew exponentially for 3τ (τ = 30 seconds), after which the disturbance saturated while still within closed field lines; 5) There was no signature in the aurora indicating a fast flow preceding and causing the 0507 UT onset; 6) The foot points of THEMIS E, D, B, and A were all in or shifted towards midnight (due to the effects of field-aligned currents) from the initial brightening region; 7) The dipolarization front moved across THEMIS D, B, A, and then E in order, indicating outward radial and/or duskward azimuthal evolution.

3. Discussion

[11] As stated in the data section, prior to the optical onset at ~0507, there was no auroral activity poleward of the onset arc to indicate a mid-tail process that caused the inner CPS disturbance and optical onset. The brightening of the arc occurred along ~1 MLT hour. The foot points of THEMIS A, B, D, and E were either in or east (towards midnight) of that region. The dipolarization front passed the satellites starting with THEMIS D, then B, A, and finally E (one minute later). Given the footprint locations, the ordering that would be expected as a consequence of azimuthal propagation away from the initial brightening would be E, then A, B, and D (e.g., eastward across the satellites). The lack of activity prior to the onset poleward of the arc that brightened, longitudinal extent of the initial brightening, and ordering of the dipolarization as seen by the satellites, lead us to conclude that the substorm began with the brightening on field lines earthward of, and then propagated radially outwards across, the four THEMIS satellites. Given that the first sign of the substorm at a satellite was at 050750 UT, the optical brightening occurred at ~0507 UT, assuming at least 30 seconds for the onset information to propagate to the ionosphere, and considering it took ~1 minute for the disturbance to propagate from THEMIS D/B/A to THEMIS E, we infer the onset occurred on field lines threading the neutral sheet roughly 7–8 Re from the Earth (consistent with the average radial location of the start of dispersionless injection based on multipoint in situ observations (E. Spanswick et al., Injection region propa-

gation beyond geosynchronous orbit, manuscript in preparation, 2008)). Finally, the onset occurred relatively far from the open-closed field-line boundary, near the transition from tail-like to dipolar field lines, based on consideration of the NORSTAR MSP and THEMIS ASI observations. We conclude that this onset is consistent with the CD scenario described in the introduction.

[12] Asserting the onset was ''CD-type'' describes where the field lines on which the optical onset mapped to in the CPS (namely near the dipolar/tail-like transition), and lack of evidence suggesting a fast flow (or other mode of interaction) that might have communicated the effects of NER to cause CD. This does not tell us the nature of the CD. The auroral and magnetotail evolution will be useful in that regard. The proton auroral fading on a time scale of ~10 minutes, and electron auroral fading (e.g., the shutting off of the electron arc) on a timescale of ~2 minutes are suggestive of a two step process, with the electron auroral fading corresponding to ''runaway'' growth at the end of the growth phase [see *Ohtani et al.*, 1991]. The initial brightening across ~1 MLT hour occurred on the part of the growth phase arc closest to the bright proton aurora which in turn corresponds to the transition between dipolar and tail-like topologies [*Samson et al.*, 1992]. The localized region wherein the preexisting arc is close to the proton aurora is consistent with an azimuthally localized region of stretching in the magnetotail which in turn brought an unstable gradient or boundary in the CPS close to the inner edge of the plasma sheet, giving a preferential region for onset to occur. Azimuthally localized stretching has been suggested in previous studies [*Jayachandran et al.*, 2005], but has not been so clearly demonstrated in any event. The m~120 azimuthal structure that arose on the arc in the expansion phase is possibly a manifestation of a magnetotail wave mode that grew in that stretched slot [see *Liang et al.*, 2008]. The linear growth with $\tau \sim 30$ seconds and saturation are suggestive of shear flow ballooning.

[13] It is universally accepted that optical onset begins on field lines threading a preexisting or newly formed auroral arc [*Akasofu*, 1964; *Lyons et al.*, 2002]. For a CD-type substorm, this arc is the ionospheric counterpart of whatever magnetospheric feature on which the instability develops. It is of critical importance for understanding of the substorm onset to establish the connection between auroral arcs and their magnetospheric counterparts. Coordinated THEMIS ASI and in situ observations will provide us the opportunity to make this connection.

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References

Akasofu, S.-I. (1964), The development of the auroral substorm, *Planet. Space Sci.*, *19*, 10.

Angelopoulos, V., et al. (2008), The THEMIS mission, *Space Sci. Rev.*, doi:10.1007/s11214-008-9336-1.

Angelopoulos, V., F. Mozer, T. Mukai, K. Tsuruda, S. Kokubun, and T. Hughes (1999), On the relationship between bursty bulk flows, current disruption, and substorms, *Geophys. Res. Lett.*, *26*, 2841.

Auster, U., et al. (2008), The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, doi:10.1007/s11214-008-9365-9.

Baker, D. N., T. Pulkkinen, V. Angelopoulos, W. Baumjohann, and R. McPherron (1996), Neutral line model of substorms: Past results and present view, *J. Geophys. Res.*, *101*, 12,975.

Blanchard, G. T., L. R. Lyons, J. C. Samson, and F. J. Rich (1995), Locating the polar cap boundary from observations of 6300 Å auroral emission, *J. Geophys. Res.*, *100*, 7855.

Donovan, E. (1993), Modeling the magnetic effects of field-aligned currents, *J. Geophys. Res.*, *98*, 13,529.

Donovan, E., et al. (2006), The THEMIS all-sky imaging array-system design and initial results from the prototype imager, *J. Atmos. Sol. Terr. Phys.*, *68*, 1472.

Jayachandran, P. T., E. F. Donovan, J. W. MacDougall, D. R. Moorcroft, K. Liou, P. T. Newell, and J.-P. St-Maurice (2005), Global and local equatorward expansion of the ion auroral oval before substorm onsets, *J. Geophys. Res.*, *110*, A05204, doi:10.1029/2004JA010837.

Liang, J., et al. (2008), Intensification of preexisting auroral arc at substorm expansion onset: Wave-like disruption during the first tens of seconds, *Geophys. Res. Lett.*, *35*, L17S19, doi:10.1029/2008GL033666.

Liu, W. W., E. F. Donovan, J. Liang, I. Voronkov, E. Spanswick, P. T. Jayachandran, B. Jackel, and M. Meurant (2007), On the equatorward motion and fading of proton aurora during substorm growth phase, *J. Geophys. Res.*, *112*, A10217, doi:10.1029/2007JA012495.

Lui, A. T. Y. (1996), Current disruption in the inner magnetosphere: Observations and models, *J. Geophys. Res.*, *101*, 13,067.

Lui, A. T. Y., and J. R. Burrows (1978), On the location of auroral arcs near substorm onset, *J. Geophys. Res.*, *83*, 3342.

Lyons, L. R., I. O. Voronkov, E. F. Donovan, and E. Zesta (2002), Relation of substorm breakup arc to other growth-phase auroral arcs, *J. Geophys. Res.*, *107*(A11), 1390, doi:10.1029/2002JA009317.

Mende, S. B., et al. (2008), The THEMIS array of ground based observatories for the study of auroral substorms, *Space Sci. Rev.*, doi:10.1007/s11214-008-9380.

Ohtani, S., K. Takahashi, L. J. Zanetti, T. A. Potemra, R. W. McEntire, and T. Iijima (1991), Tail current disruption in the geosynchronous region, in *Magnetospheric Substorms, AGU Geophys. Monogr. Ser.*, vol. 64, edited by J. R. Kan et al., pp. 131–137, AGU, Washington, D. C.

Roux, A., S. Perraut, P. Robert, A. Morane, A. Pedersen, A. Korth, G. Kremser, B. Aparicio, D. Rodgers, and R. Pellinen (1991), Plasma sheet instability related to the westward traveling surge, *J. Geophys. Res.*, *96*, 17,697.

Samson, J. C., et al. (1992), Proton aurora and substorm intensification, *J. Geophys. Res. Lett.*, *19*, 2167.

Shiokawa, K., et al. (1998), High-speed ion flow, substorm current wedge, and multiple Pi 2 pulsations, *J. Geophys. Res.*, *103*, 4491.

Tsyganenko, N. A. (1989), A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, *37*, 5.

Zesta, E., L. R. Lyons, and E. Donovan (2000), The auroral signature of earthward flow bursts observed in the magnetotail, *Geophys. Res. Lett.*, *27*, 3241.

V. Angelopoulos and C. T. Russell, IGPP, UCLA, Box 951567, Los Angeles, CA 90095, USA.

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

G. Baker, E. Donovan, M. Greffen, B. Jackel, E. Spanswick, and T. Trondsen, Department of Physics and Astronomy, University of Calgary, Calgary, AB T2N 1N4, Canada. (edonovan@ucalgary.ca)

C. W. Carlson, H. U. Frey, A. Keiling, J. P. McFadden, and S. B. Mende, Space Sciences Laboratory, University of California, Berkeley, 7 Gauss Way, Berkeley, CA 94720-7450, USA.

M. Connors and I. Voronkov, Athabasca University Geophysical Observatory, Athabasca University, Athabasca, AB T9S 3A3, Canada.

K. Hayashi, Department of Earth and Planetary Physics, University of Tokyo, Bunkyo-ku, Tokyo, Japan.

J. Liang and W. Liu, Space Sciences Division, Canadian Space Agency, 6767 Route de l'Aéroport, Saint-Hubert, QC J3Y 8Y9, Canada.

I. J. Rae, Department of Physics, University of Alberta, Edmonton, AB T6G 2R3, Canada.

K. Sakaguchi and K. Shiokawa, Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan.

M. Syrjäsuo, Finnish Meteorological Institute, Helsinki FI-00101, Finland.

J. A. Wild, Department of Communication Systems, Lancaster University, Lancaster, LA1 4WA, UK.