

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL083070

Key Points:

- Azimuthally drifting interchange heads in the near-Earth plasma sheet may detach and propagate earthward
- Detached interchange heads are seen as localized dipolarization fronts amidst azimuthally drifting interchange heads
- The detachments cause ionospheric pseudo-breakups with local current system and auroral bright spots originating from azimuthal beads/rays

Supporting Information:

- Supporting Information S1
- Movie S1
- Movie S2
- Movie S3
- Movie S4

Correspondence to:

E. V. Panov,
evgeny.panov@oeaw.ac.at

Citation:

Panov, E. V., Baumjohann, W., Nakamura, R., Pritchett, P. L., Weygand, J. M., & Kubyshkina, M. V. (2019). Ionospheric footprints of detached magnetotail interchange heads. *Geophysical Research Letters*, 46, 7237–7247. <https://doi.org/10.1029/2019GL083070>

Received 29 MAR 2019

Accepted 28 MAY 2019

Accepted article online 4 JUN 2019

Published online 15 JUL 2019

Ionospheric Footprints of Detached Magnetotail Interchange Heads

E. V. Panov¹ , W. Baumjohann¹ , R. Nakamura¹ , P. L. Pritchett² , J. M. Weygand³ ,
and M. V. Kubyshkina⁴ 

¹Space Research Institute, Austrian Academy of Sciences, Graz, Austria, ²Department of Physics and Astronomy, University of California, Los Angeles, CA, USA, ³Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, USA, ⁴Institute of Physics, St. Petersburg State University, St. Petersburg, Russia

Abstract Pritchett and Coroniti (2011, <https://doi.org/10.1029/2011GL047527>, 2013, <https://doi.org/10.1029/2012JA018143>) have predicted that the kinetic ballooning/interchange instability (BICI) can provoke reconnection onsets that lead to detached azimuthally thin earthward intrusions (heads) of depleted plasma tubes when $\beta_{eq} \leq 100$. Such detached BICI heads would be seen as localized earthward-propagating dipolarization fronts. Using Time History of Events and Macroscale Interactions during Substorms observations in the plasma sheet at $X_{GSM} \approx -11R_E$ and conjugate All-Sky Imager and magnetometer networks observations on the ground, we show four examples when prominent dipolarization fronts with moderate earthward flows were observed amidst azimuthally drifting interchange heads and concurrently with the ionospheric current intensifications near Time History of Events and Macroscale Interactions during Substorms footprints and auroral bright spots originating from dimmer azimuthal beads/rays. These events support the idea that some of the BICI heads detach from the region with reversed radial gradient of B_z due to local reconnection. The detached BICI heads propagate earthward-driving ionospheric pseudo-breakups.

Plain Language Summary The Earth's magnetotail periodically accumulates energy in form of the magnetic flux in the tail lobes and dumps the energy as fast earthward and tailward plasma flows, which are produced by magnetic reconnection. Yet there is no consensus on what magnetotail processes may lead to reconnection. Examples of multiprobe space observations are used to reveal the possible process that might be important for azimuthally localized reconnection in the tail that leads to pseudo-breakups in aurora and local ionospheric current systems. The examples show the appearance of earthward-propagating reconnection (dipolarization) fronts amidst azimuthally propagating clumps of more dipolar field lines that were produced by an instability which was predicted to lead to localized reconnection by earlier plasma computer simulations. The conjugate ground auroral and magnetic field observations support the reconnection fronts' origin hypothesis.

1. Introduction

As multispacecraft observations have revealed (Angelopoulos et al., 2008), fast earthward and tailward plasma flows in the Earth's magnetotail are produced by magnetic reconnection. To date, a number of ideas have been proposed where and what processes may lead to the magnetotail reconnection (Sitnov et al., 2019). It has been theoretically predicted (Hau et al., 1989, 1991; Hsieh & Otto, 2015; Pritchett & Coroniti, 1994, 1995) and supported by some observations (e.g., Panov & Pritchett, 2018a; Sergeev et al., 2018, and references therein) that magnetic field minima may be formed in the transition region between the dipole and tail fields around $X_{GSM} \approx -11R_E$. In such magnetotail configurations, global reconnection is suggested to occur due to magnetohydrodynamic “ B_z -hump” instability (Birn et al., 2018; Merkin & Sitnov, 2016; Sitnov et al., 2009, 2013) and is also seen in kinetic simulations (Pritchett, 2015; Sitnov et al., 2017).

Kinetic Particle-In-Cell (PIC) simulations of current sheets with tailward gradients of B_z , part of magnetotail configurations with a magnetic field minimum, have revealed the growth of azimuthally confined earthward-intruding depleted plasma tubes (heads) with field-aligned electron flows in the course of the Ballooning/InterChange Instability (BICI) development (Pritchett & Coroniti, 2010; Sitnov et al., 2014). Some

of the BICI heads may detach from the region of the tailward B_Z gradient in the process of azimuthally localized reconnection (Pritchett & Coroniti, 2011, 2013). In a strongly stretched configuration where the equatorial plasma beta $\beta_{eq} > 500$, a global disruption of the thinned current sheet was predicted to occur (Pritchett & Coroniti, 2011; Pritchett et al., 2014).

Both B_Z -hump and BICI (with $\beta_{eq} > 500$) instabilities were successful in reproducing the basic signatures of global earthward-propagating reconnection (dipolarization) fronts (DFs; Ohtani, 1998; Nakamura et al., 2002; Runov et al., 2009). However, the majority of the observed DFs are only 1–3 R_E wide (with 3 R_E at geosynchronous equatorial orbit according to Figure 3 in Liu et al., 2015). Pritchett et al. (2014) suggested that separate detached BICI heads, which actually have similar azimuthal scale, could be the source of such narrow DFs.

DFs are embedded in bursty bulk flows (Baumjohann et al., 1990) and are related with auroral intensifications in the ionosphere (Nakamura et al., 1994, 2001). During growth phase before substorm expansion, pseudo-breakups are regularly observed and usually associated with weak magnetotail flows (McPherron et al., 1997). In the course of a pseudo-breakup, a localized current system may be formed in the conjugate ionosphere (Partamies et al., 2003). Some observations indicated that pseudo-breakups might be a consequence of a ballooning mode development in the near-Earth plasma sheet (Baumjohann et al., 2007; Sergeev et al., 2005). Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations (Panov, Sergeev, et al., 2012; Panov, Nakamura, et al., 2012) showed that sausage magnetic oscillations that propagate duskward across the near-Earth plasma sheet at $X_{GSM} \approx -11R_E$ indeed exhibit characteristic field-aligned electron flows and other BICI signatures predicted for neutral sheet simulations. As predicted for charged current sheets with a finite average E_Z directed toward the center of the plasma sheet, similar magnetic oscillations drift downward (Panov & Pritchett, 2018a, 2018b).

Motivated by the hypothesis that azimuthally drifting BICI heads may detach and propagate earthward due to local reconnection (Pritchett & Coroniti, 2011, 2013; Pritchett et al., 2014), we show examples of DFs that were observed amidst identified BICI heads. We use magnetotail observations provided by the THEMIS (Angelopoulos, 2008) probes' fluxgate magnetometers (Auster et al., 2008), electrostatic analyzers' (McFadden et al., 2008) particle detectors, and electric field instruments (Bonnell et al., 2008) between 6:00 and 7:30 UT on 14 February 2008, between 9:20 and 10:20 UT on 15 February 2008, between 5:00 and 6:00 UT on 26 February 2009, and between 6:30 and 7:30 UT on 18 April 2009. With the help of an event-tailored adapted model for field line mapping (Kubyshkina et al., 2011), we also show conjugate ground auroral and magnetic field observations. Observations of the ionospheric auroral emissions and magnetic field were provided by THEMIS All-Sky Imagers (ASI) and by a dense network of ground magnetometer arrays over Greenland and North America (Mann et al., 2008; Mende et al., 2008; Weygand et al., 2011).

2. DF Examples

Panov and Pritchett (2018a) showed that on 15 February 2008, a B_Z dip with radial size of about 2.5 Earth radii (R_E) and azimuthal size that could be as large as 10 R_E was present between 09:00 and 11:00 UT in the plasma sheet at $X_{GSM} \approx -11 R_E$. BICI heads were observed at the tailward side of the dip with $\partial B_Z / \partial X \approx -10$ nT/ R_E . Figure 1 shows THEMIS probes' plasma sheet observations on 15 February 2008 between 9:20 UT and 10:20 UT. The auroral electrojet (AE) index (top panel) was slowly growing on average from 200 nT at 9:20 UT to 400 nT at 9:55 UT. A sharp jump of the Kyoto AE index to 700 nT was observed around 10:05 UT. The jump was smoother in the THEMIS AE index. The second and third panels in Figure 1 show B_X and B_Z Geocentric Solar Magnetospheric (GSM) magnetic field components. Significant variations in B_X and B_Z were observed at P2 (green) between 9:20 and 9:50 UT (several BICI heads are highlighted by the orange text arrows in Figure 1). They were associated with the field-aligned ion and electron velocity variations (panels four [V_{ix}] and five [V_{ex}] in Figure 1). The ion velocity variation amplitude (about 200 km/s) was about 20% of the electron variation amplitude (about 1,000 km/s). Similar magnetic field variations with much smaller amplitudes were observed by the other THEMIS probes. Around 9:55 UT, P3–P5 observed a DF (highlighted by the blue text arrow in Figure 1) that was embedded in a bulk earthward flow. The flow was observed mainly by P3 and P4. According to the next panel, the ratio of the total ion and electron pressure to the magnetic field pressure (plasma β) was about 1 at the location of P2–P5 and up to 100 near the neutral plane (cf. Figure 1 in Panov & Pritchett, 2018a). According to Panov and Pritchett (2018a), the variations in B_X , B_Z , V_{ix} , and V_{ex} in Figure 1 manifested BICI heads that drifted azimuthally toward dawn at a velocity of about

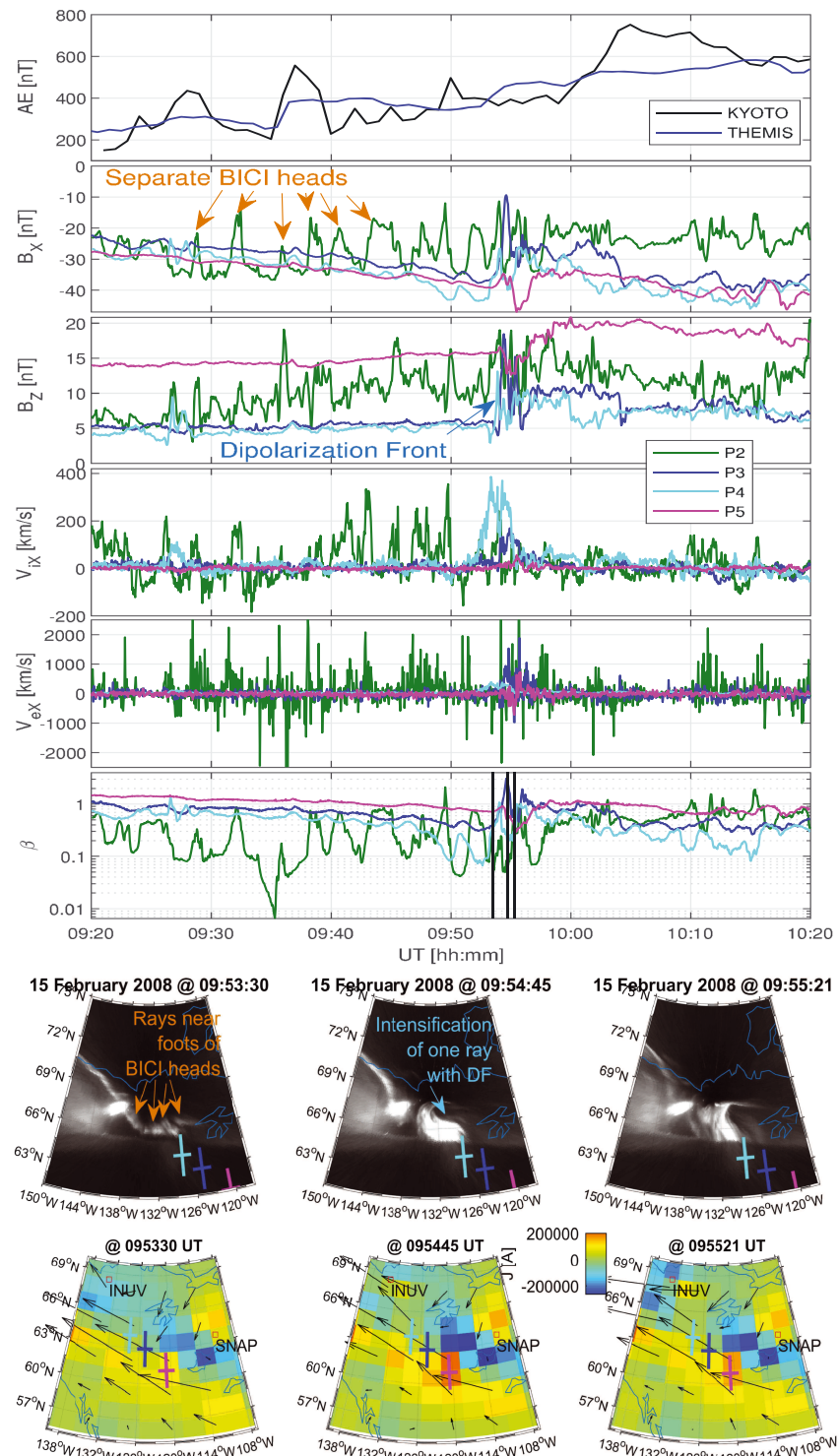


Figure 1. (top) THEMIS probes' observations on 15 February 2008 between 9:20 UT and 10:20 UT: Kyoto and THEMIS auroral electrojet indices, B_x and B_z Geocentric Solar Magnetospheric magnetic field components, X_{GSM} velocity components of ions (V_{ix}) and electrons (V_{ex}), plasma β (see legends for color coding). (middle) Aurora snapshots from All-Sky Imager at INUV and (bottom) snapshots of equivalent ionospheric currents (arrows) and the Spherical Elementary Current System current amplitudes (color: upward in reddish and downward in bluish) calculated using ground-based magnetometer array data at 9:53:30 UT, 9:54:45 UT, and 9:55:21 UT (cf. black vertical lines in the plasma β panel). The footprints of THEMIS probes as predicted by the AM-03 model are denoted by overplotted crosses. BICI = ballooning/interchange instability; THEMIS = Time History of Events and Macroscale Interactions during Substorms; INUV = Inuvik.

0.3 times the ion thermal velocity (about 200 km/s). The typical azimuthal scale of a BICI head appeared to be about $2 R_E$.

The field of view (fov) of the ASI at Inuvik, NT, Canada (three black and white snapshots in Figure 1), appeared to cover the area about 3° northward of the footprints of P3–P5 (blue, cyan, and magenta crosses). The footprints of the five THEMIS probes were predicted by the AM-03 model at 1-min cadence. The size of the crosses is 3° in both longitude and latitude, that is, significantly larger than the possible error due to, for example, an underestimated current density of the thin magnetotail current sheet (not shown here). The footprint of P2 was slightly westward from the fov western border. Between 9:20 UT and 9:50 UT, the ASI at Inuvik observed an azimuthally oriented fence of dynamic auroral rays (highlighted by the orange arrows in the first ASI snapshot in Figure 1 at 9:53:30 UT). The rays were significantly dimmer than the moonlight (the brightest spot in the snapshot at 9:53:30 UT). The moonlight is also seen in the other two snapshots at 9:54:45 UT and 9:55:21 UT in the same location. The three black vertical lines in the plasma β panel indicate times that correspond to the three ASI snapshots. At 9:54 UT (i.e., simultaneously with the DF observations in the plasma sheet), one of the auroral rays suddenly intensified into a large bright spot (snapshot at 9:54:45 UT) and moved equatorward (snapshot at 9:55:21 UT; see movie with all ASI snapshots in the supplementary material). After that, this bright spot disappeared, while dimmer rays were still observed.

We applied the 2-D Spherical Elementary Current Systems (SECSs) method (Amm & Kauristie, 2002; Weygand et al., 2011) to the magnetometer data to investigate ionospheric currents. In this method, the divergence-free elementary current system is expanded at each pole of the grid shown in Figure 2 of Weygand et al. (2011), allowing derivation of horizontal equivalent ionospheric currents (EICs). Using EICs, we calculated vertical components of the curl of EICs integrated over each grid point area. We refer to the vertical components as SECS current amplitudes (measured in amperes). Under assumption that the gradient in the ionospheric conductance perpendicular to the electric field is zero, the SECS current amplitudes are expected to be proportional to field-aligned currents (Amm & Kauristie, 2002). The factor of proportionality between field-aligned currents and the SECS current amplitudes is the Hall-to-Pedersen conductance ratio. The ionospheric electric current system (three color snapshots at the bottom of Figure 1 at the same times as the ASI snapshots above; EICs shown by arrows and SECS current amplitudes by color: upward in reddish and downward in bluish) reveals weak azimuthally oriented spots of upward/downward currents with small westward electrojet (horizontal) current between them. The ionospheric currents significantly intensified around the appearance time of the DF in the plasma sheet. The upward current location coincided with the location of the bright spot in the ASI observations. Note that the center of the current system was near the eastern border of the ASI fov. Therefore, we shifted the area of the EICs/SECS snapshots by 10° eastward in longitude for better visibility.

The next three figures show THEMIS plasma sheet observations, as well as ground ASI and ionospheric current observations in the same format as Figure 1 on 26 February 2009 between 5:00 UT and 6:00 UT (Figure 2), on 14 February 2008 between 6:00 UT and 7:30 UT (Figure 3), and on 18 April 2009 between 6:30 UT and 7:30 UT (Figure 4). During the three events, THEMIS probes observed signatures of BICI heads (highlighted by orange text arrows) and DFs (highlighted by blue text arrows). On the ground, ASI imagers observed rays or beads during BICI head signatures observations by THEMIS (left ASI snapshots in Figures 2–4) and sudden intensification of one of the rays or beads around the DF appearance in the plasma sheet (middle and right ASI snapshots in Figures 2–4). See captions in Figures 2–4 for ASI names. The locations of intensified upward current spots coincided with the locations of the bright spots in the ASI observations (bottom snapshots in Figures 2–4).

In the event on 26 February 2009 between 5:00 UT and 6:00 UT (Figure 2), the AE index (top panel) was very small (between 10 and 70 nT). In such a relaxed magnetotail, the equatorial B_z appeared to be rather large (about 5 nT). During this event, the oscillation amplitudes in B_x were comparable to those in B_z (cf. the second and third panels in Figure 2). This is contrasting with the previous reports on BICI heads (Panov & Pritchett, 2018a; Panov, Sergeev, et al., 2012), where δB_x was significantly larger than δB_z . However, this is in a better agreement with the PIC simulations of BICI heads, where δB_x and δB_z were predicted to be comparable. Hence, a large value for the initial B_z field, which was chosen because of numerical constraints in the PIC simulations, could indeed be the reason for larger δB_x in the observations with smaller equatorial B_z values, as suggested in Panov and Pritchett (2018a) and Panov, Sergeev, et al. (2012).

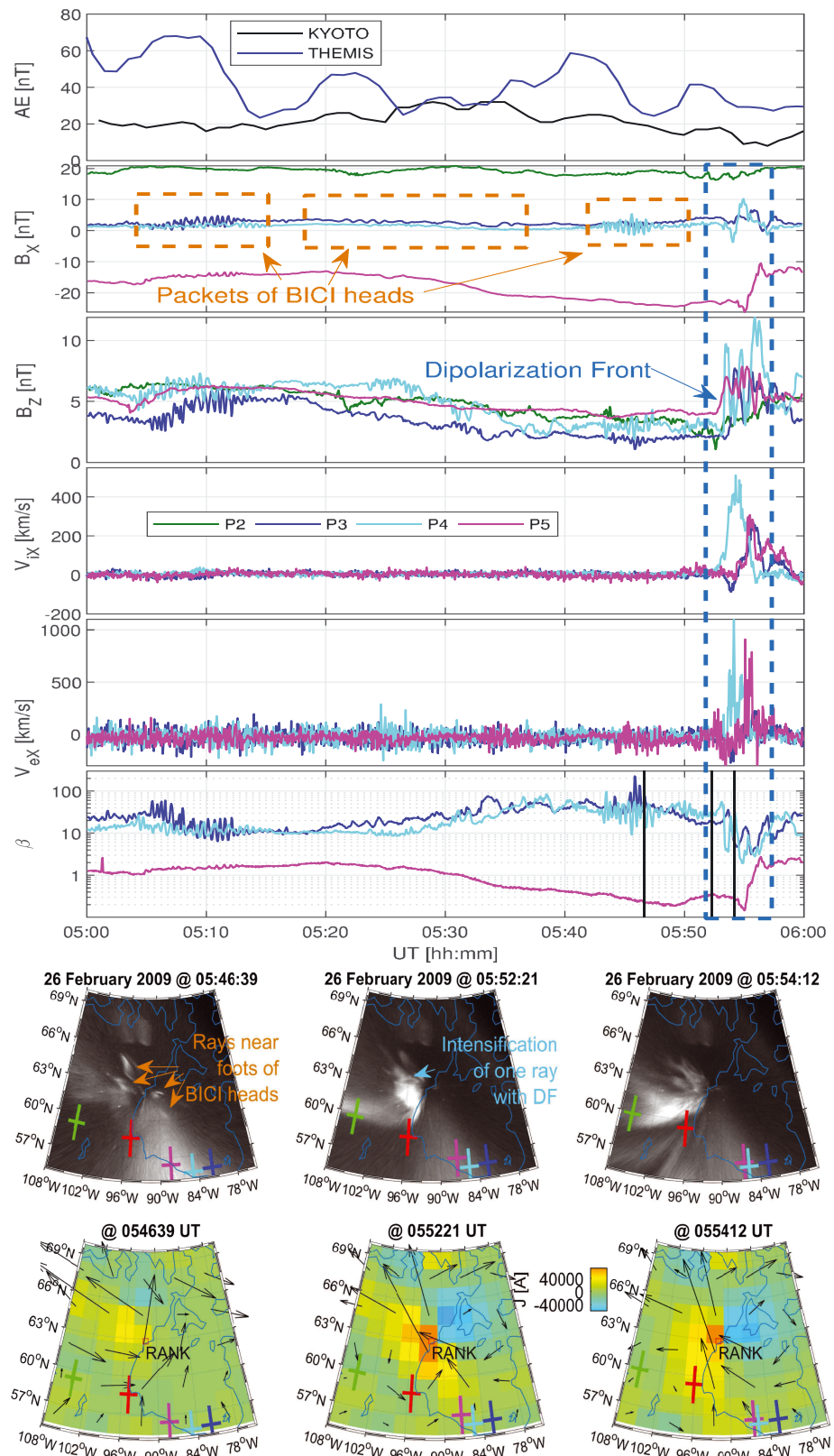


Figure 2. THEMIS, ASI, and equivalent ionospheric current/Spherical Elementary Current System observations on 26 February 2009 between 5:00 UT and 6:00 UT. The figure has the same format as Figure 1. The ASI data were provided by ASI at Rankin Inlet, NU, Canada. BICI = ballooning/interchange instability; THEMIS = Time History of Events and Macroscale Interactions during Substorms; ASI = All-Sky Imager.

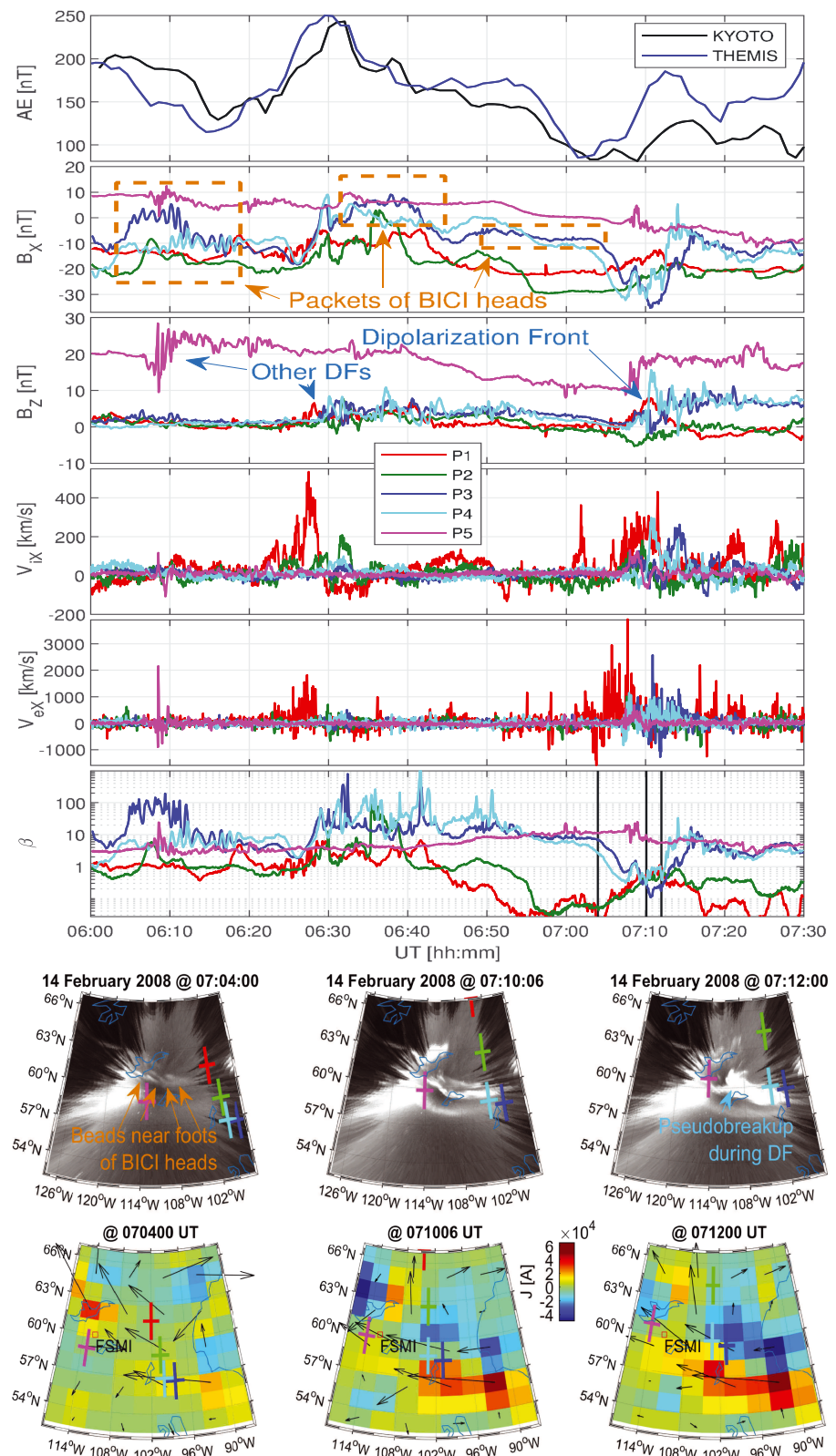


Figure 3. THEMIS, ASI, and equivalent ionospheric current/Spherical Elementary Current System observations on 14 February 2008 between 6:00 UT and 7:30 UT. The figure has the same format as Figure 1. The ASI data were provided by ASI at Fort Smith, NT, Canada. BICI = ballooning/interchange instability; THEMIS = Time History of Events and Macroscale Interactions during Substorms; ASI = All-Sky Imager.

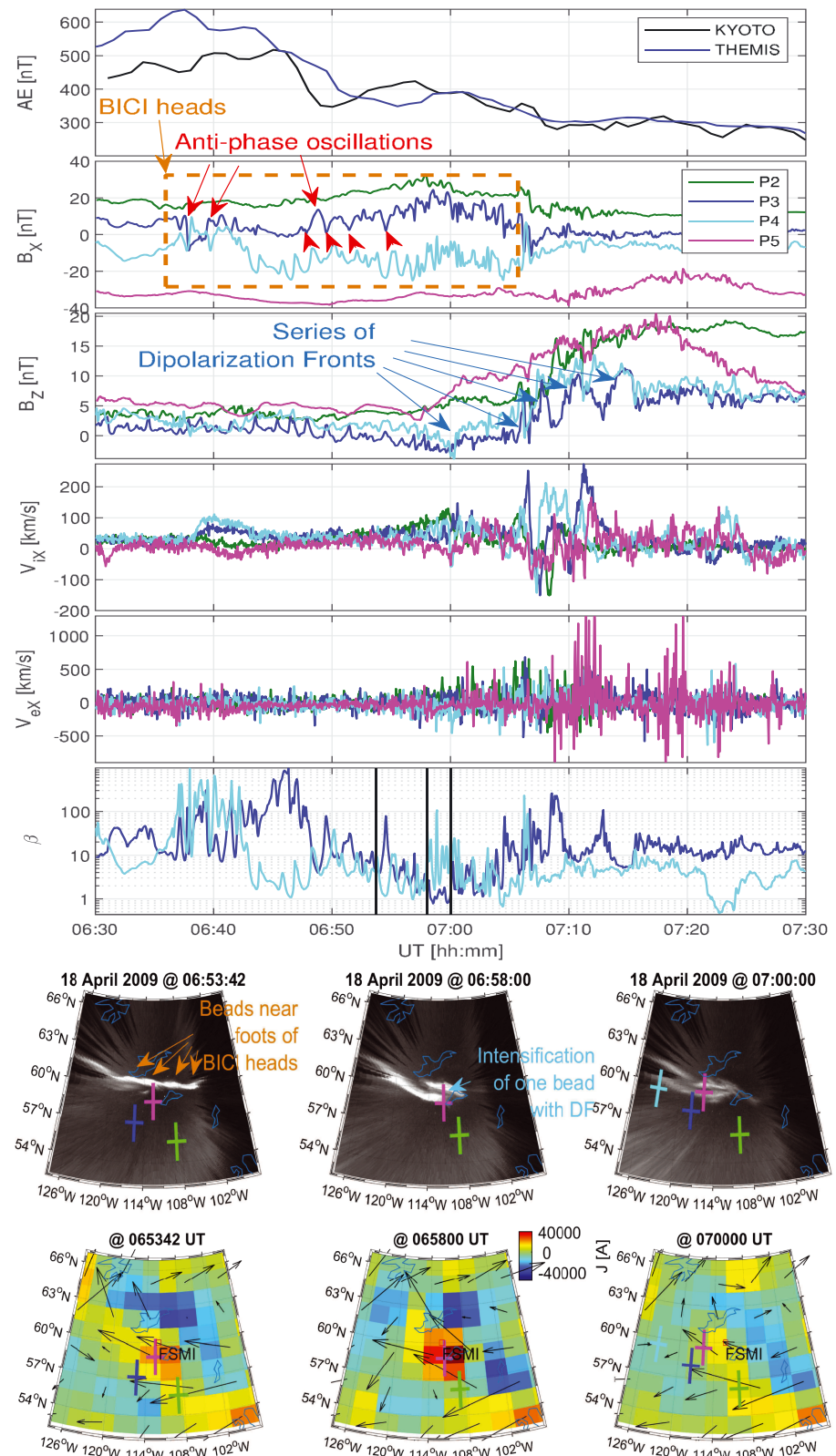


Figure 4. THEMIS, ASI, and equivalent ionospheric current/Spherical Elementary Current System observations on 18 April 2009 between 6:30 UT and 7:30 UT. The figure has the same format as Figure 1. The ASI data were provided by ASI at Fort Smith, NT, Canada. BICI = ballooning/interchange instability; THEMIS = Time History of Events and Macroscale Interactions during Substorms; ASI = All-Sky Imager.

Using a wave train observed in B_X at both P3 and P4 between 5:44:00 UT and 5:48:00 UT, we found that P3 data were delayed after P4 by about 8 s. One oscillation period in the wave train was about 25 s. The major separation between P3 and P4 was 6,677 km in the Y_{GSM} direction. The resulting propagation velocity of the wave train from P4 to P3 (dawnward) was about 6,677 km/8 s $\approx$ 835 km/s. This value is between 1.2 and 1.7 of the thermal ion velocity (between 500 and 700 km/s). The BICI head size was about 1.6 R_E , which is close to the size of a typical BICI head on 15 February 2008 between 09:00 and 11:00 UT (Panov & Pritchett, 2018a). This is in agreement with the fact that the ASI imagers observed bright spots of similar sizes in the events in Figures 1 and 2 since the size of the auroral bright spot is expected to be dependent on the azimuthal size of the DF. Similar to the event in Figure 1, the plasma β did not exceed $\approx$ 100 near the neutral plane.

Figure 3 shows an example of a broader DF that was observed by azimuthally separated probes P3–P5 around 7:10 UT and coincided with the appearance of an azimuthally broader bright spot and current system in the ionosphere near P3–P5 footprints. Note that signatures of other (narrower) DFs (indicated by blue arrows in the B_Z panel in Figure 3) were observed also at 6:08 UT by P5 and at 6:30 UT by P1–P4. Using a wave train observed in B_X at P3 and P4 between 6:12 UT and 6:21 UT, we found that P4 data were delayed after P3 by about 8 s. One oscillation period in the wave train was about 55 s. The major separation between P3 and P4 was 5,699 km in the Y_{GSM} direction. The resulting propagation velocity of the wave train from P3 to P4 (duskward) was about 5,699 km/8 s $\approx$ 712 km/s. This value was about 1.2 times the thermal ion velocity (about 600 km/s). The BICI head size (scale of the half period of the wave train) was about 3 R_E . The plasma β was around 100 near the neutral plane (cf. plasma β at P3 around 6:10 UT when B_X was about zero). In the ASI snapshot in Figure 3 at 7:04:00 UT (at the time of the BICI head signatures observation in the plasma sheet), there were observed azimuthally separated beads between the footprints of P5 and P3/P4. Two other ASI snapshots in Figure 3 (around the time of the DF observation by P3–P5 in the plasma sheet) revealed an azimuthally broad bright spot in the location of the former beads. The bright spot location coincided with the location of the upward (reddish) current revealed by the SECS snapshots (bottom row in Figure 3). The brightest part of the upward current spot extended further eastward beyond the ASI's fov. We shifted the area of the SECS snapshots in Figure 3 by 10° eastward for better visibility. Such ASI and SECS observations suggest that the DF was formed by simultaneous detachment of several BICI heads.

Figure 4 shows an example in which signatures of the BICI heads in THEMIS observations were followed by a series of DFs (cf. orange and blue text arrows). The first DF was detected between 6:58 UT and 7:02 UT as a dip that was followed by a growth in B_Z (third panel in Figure 4) and an earthward flow of up to 140 km/s at P4 (fourth panel in Figure 4). Several more DFs and faster flows (up to 250 km/s) were observed by P2–P5 between 7:05 UT and 7:13 UT. Using a wave train observed in B_X at P3 and P4 between 6:45 UT and 7:00 UT, we found that P4 data were delayed after P3 by about 22 s. One oscillation period in the wave train was about 100 s. The major separation between P3 and P4 was 4,226 km in the Y_{GSM} direction. The resulting propagation velocity of the wave train from P3 to P4 (duskward) was about 4,226 km/22 s $\approx$ 192 km/s. This value was about 0.3 times the thermal ion velocity (about 600 km/s). The BICI head size (scale of the half period of the wave train) was about 1.5 R_E . Probes P3 and P4 were located at different hemispheres. This allowed to directly observe the sausage magnetic field oscillations, which is another signature of BICI heads (seen as antiphase B_X oscillations on the two sides from the neutral sheet [close to $B_X = 0$] at P3 and P4; similar observations were reported in Panov, Nakamura, et al., 2012). During this event, the equatorial plasma β was larger than in the other events, reaching values up to several hundreds (cf. plasma β at P3 and P4 between 6:35 UT and 6:50 UT). According to P3 B_X and plasma β , after 7:10 UT, the equatorial plasma β decreased to 10. In the ASI snapshot in Figure 4 at 6:53:42 UT (at the time of the BICI head signatures observation in the plasma sheet), there were observed azimuthally separated beads near the footprints of P3–P5. Two other ASI snapshots in Figure 4 (around the time of the first DF observation by P3–P5 in the plasma sheet at 6:58 UT) revealed a bright spot in the location of one of the former beads. The bright spot location coincided with the location of the upward (reddish) current revealed by the SECS snapshots (bottom row in Figure 4). Both the bright spot and the SECS upward current amplitude decreased after the DF. Note that similar bright spots were observed in slightly different locations together with the appearance of other DFs between 7:05 UT and 7:13 UT (cf. the video with all ASI snapshots between 6:30 UT and 7:30 UT in the supplementary materials). Such ASI and SECS observations suggest that several DFs were formed by a series of sequentially detached BICI heads. In this case the ionospheric response was similar to the response during oscillatory flow braking (Panov et al., 2016), when every subsequent earthward flow was a result of multiple overshoot and rebound of the original fast flow.

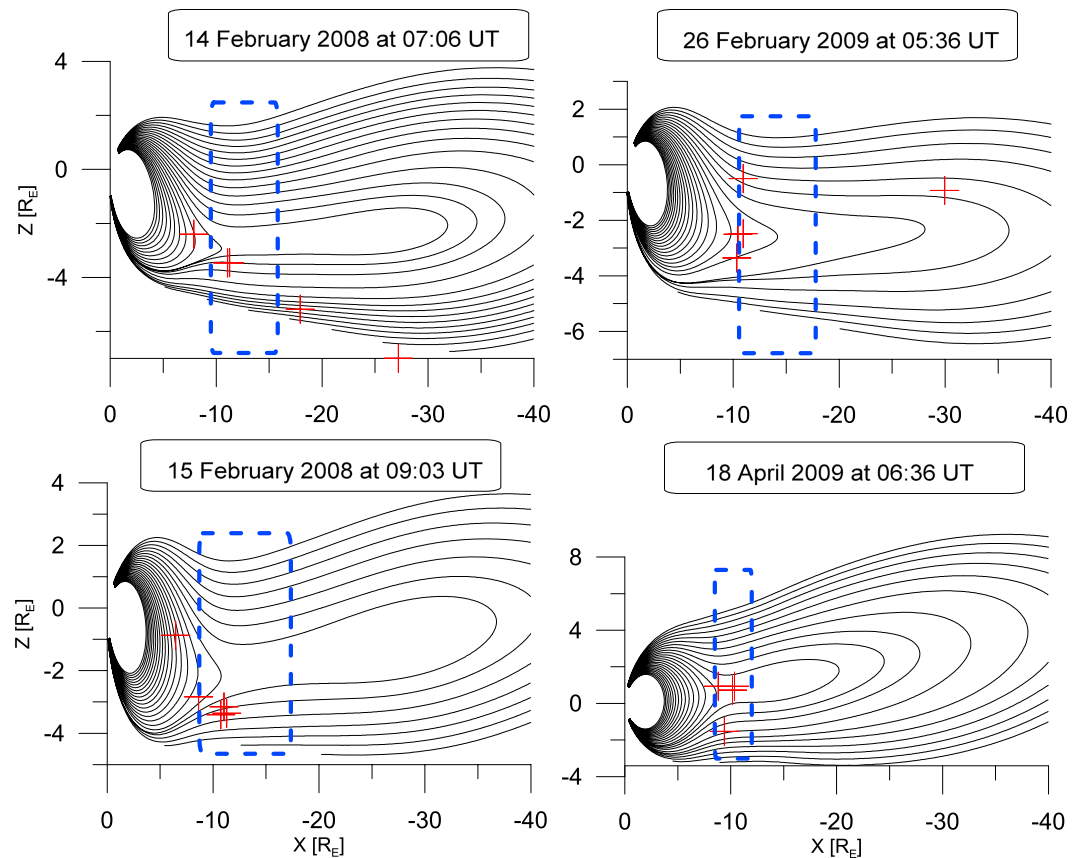


Figure 5. Magnetic field lines according to the AM-03 model shown in the noon meridian Geocentric Solar Magnetospheric plane on 14 February 2008 at 7:06 UT (top left), on 15 February 2008 at 9:03 UT (bottom left), on 26 February 2009 at 5:36 UT (top right), and on 18 April 2009 at 6:36 UT (bottom right). The red crosses denote Time History of Events and Macroscale Interactions during Substorms probes locations whose magnetic field data were used in the model. The area where $\partial B_z / \partial X$ changes sign around B_z minimum is indicated by the blue dashed rectangles.

Two of the above examples of BICI heads showed duskward propagation (Figures 3 and 4), which is the signature of charge neutral current sheet (see Pritchett & Coroniti, 2010, 2013, for PIC simulations and Panov, Sergeev, et al., 2012, for comparison with in situ observations). In contrast, Figures 1 and 2 showed dawnward propagation of the magnetotail structures with BICI heads signatures. The dawnward propagation of BICI heads was predicted (Nishimura et al., 2016) and advocated to occur (Panov & Pritchett, 2018a) in the plasma sheet with a thin negatively charged current layer (Pritchett & Coroniti, 1994, 1995).

In both neutral and charged sheet cases, the necessary condition for BICI head generation was tailward gradient of the equatorial B_z in the plasma sheet. Figure 5 shows the magnetic field lines according to the AM-03 model in the noon meridian GSM plane on 14 February 2008 at 7:06 UT (top left), on 15 February 2008 at 9:03 UT (bottom left), on 26 February 2009 at 5:36 UT (top right), and on 18 April 2009 at 6:36 UT (bottom right). The red crosses denote THEMIS probes' locations whose magnetic field data were used in the AM-03 model. The magnetotail structure in all four snapshots of Figure 5 indeed reveals magnetotail regions with a reversed B_z gradient (the area where $\partial B_z / \partial X$ changes sign around B_z minima is indicated by the blue dashed rectangles). These regions were found at $-25 R_E < X_{GSM} < -10 R_E$ downtail, with the strongest gradients expected in the transition region between the Earth's dipole field lines and the stretched field lines of the magnetotail, that is, around $10 R_E$ downtail.

The three assumptions, (i) on the current sheet charging, (ii) on the number of simultaneous BICI head detachments at different azimuthal locations, and (iii) on whether several detachments occurred sequentially, are in line with the “detached BICI head” hypothesis. The hypothesis explains the dynamics of the near-Earth plasma sheet in the course of the BICI development and the ionospheric response in the present events.

In at least 100 events, two THEMIS probes observed BICI head signatures similar to those in Figures 1-4 during the first five magnetotail seasons. This occurrence rate would be comparable with the known occurrence rates for DFs (e.g., Schmid et al., 2011). The total observational time for each of these events is significantly longer than for DFs, because the typical crossing time of a DF is about the crossing time of one BICI head. Most of time BICI heads occurred either prior to substorms (Panov, Sergeev, et al., 2012) or without a substorm (present study). The present observations suggest that BICI heads may be as significant in the earthward transport of magnetic flux and plasma as rapid flux transport by the DFs (e.g., Angelopoulos et al., 1996) and play a role in initiating rapid flux transport events.

3. Conclusions

Using THEMIS observations in the plasma sheet and conjugate ASI and magnetometer networks observations on the ground, we showed examples of prominent DFs with moderate earthward flows that were observed amidst azimuthally drifting interchange heads at $X_{GSM} \approx -11 R_E$. The conjugate ground observations revealed ionospheric current intensifications and growth of auroral bright spots out of dimmer azimuthal beads/rays near THEMIS footprints. The DFs can be interpreted as separate BICI heads that detached from the region with reversed radial gradient of B_z and propagated earthward-driving ionospheric pseudo-breakups.

References

- Amm, O., & Kauristie, K. (2002). Ionospheric signatures Of bursty bulk flows. *Surveys in Geophysics*, 23, 1–32. <https://doi.org/10.1023/A:1014871323023>
- Angelopoulos, V. (2008). The THEMIS Mission. *Space Science Reviews*, 141, 5–34. <https://doi.org/10.1007/s11214-008-9336-1>
- Angelopoulos, V., Coroniti, F. V., Kennel, C. F., Kivelson, M. G., Walker, R. J., Russell, C. T., et al. (1996). Multipoint analysis of a bursty bulk flow event on April 11, 1985. *Journal of Geophysical Research*, 101, 4967–4989. <https://doi.org/10.1029/95JA02722>
- Angelopoulos, V., McFadden, J. P., Larson, D., Carlson, C. W., Mende, S. B., Frey, H., et al. (2008). Tail reconnection triggering substorm onset. *Science*, 321, 931–935. <https://doi.org/10.1126/science.1160495>
- Auster, H. U., Glassmeier, K. H., Magnes, W., Aydogar, O., Baumjohann, W., Constantinescu, D., et al. (2008). The THEMIS Fluxgate Magnetometer. *Space Science Reviews*, 141, 235–264. <https://doi.org/10.1007/s11214-008-9365-9>
- Baumjohann, W., Paschmann, G., & Luehr, H. (1990). Characteristics of high-speed ion flows in the plasma sheet. *Journal of Geophysical Research*, 95, 3801–3809. <https://doi.org/10.1029/JA095iA04p03801>
- Baumjohann, W., Roux, A., Le Contel, O., Nakamura, R., Birn, J., Hoshino, M., et al. (2007). Dynamics of thin current sheets: Cluster observations. *Annals of Geophysics*, 25, 1365–1389. <https://doi.org/10.5194/angeo-25-1365-2007>
- Birn, J., Merkin, J. G., Sitnov, M. I., & Otto, A. (2018). MHD stability of magnetotail configurations with a B_z hump. *Journal of Geophysical Research: Space Physics*, 123, 3477–3492. <https://doi.org/10.1029/2018JA025290>
- Bonnell, J. W., Mozer, F. S., Delory, G. T., Hull, A. J., Ergun, R. E., Cully, C. M., et al. (2008). The Electric Field Instrument (EFI) for THEMIS. *Space Science Reviews*, 141, 303–341. <https://doi.org/10.1007/s11214-008-9469-2>
- Hau, L.-N. (1991). Effects of steady state adiabatic convection on the configuration of the near-earth plasma sheet. II. *Journal of Geophysical Research*, 96, 5591–5596. <https://doi.org/10.1029/90JA02619>
- Hau, L.-N., Wolf, R. A., Voigt, G.-H., & Wu, C. C. (1989). Steady state magnetic field configurations for the Earth's magnetotail. *Journal of Geophysical Research*, 94, 1303–1316. <https://doi.org/10.1029/JA094iA02p01303>
- Hsieh, M.-S., & Otto, A. (2015). Thin current sheet formation in response to the loading and the depletion of magnetic flux during the substorm growth phase. *Journal of Geophysical Research: Space Physics*, 120, 4264–4278. <https://doi.org/10.1002/2014JA020925>
- Kubyskhina, M., Sergeev, V., Tsyganenko, N., Angelopoulos, V., Runov, A., Donovan, E., et al. (2011). Time-dependent magnetospheric configuration and breakup mapping during a substorm. *Journal of Geophysical Research*, 116, A00127. <https://doi.org/10.1029/2010JA015882>
- Liu, J., Angelopoulos, V., Zhou, X.-Z., Yao, Z.-H., & Runov, A. (2015). Cross-tail expansion of dipolarizing flux bundles. *Journal of Geophysical Research: Space Physics*, 120, 2516–2530. <https://doi.org/10.1002/2015JA020997>
- Mann, I. R., Milling, D. K., Rae, I. J., Ozeke, L. G., Kale, A., Kale, Z. C., et al. (2008). The upgraded CARISMA magnetometer array in the THEMIS era. *Space Science Reviews*, 141, 413–451. <https://doi.org/10.1007/s11214-008-9457-6>
- McFadden, J. P., Carlson, C. W., Larson, D., Ludlam, M., Abiad, R., Elliott, B., et al. (2008). The THEMIS ESA plasma instrument and in-flight calibration. *Space Science Reviews*, 141, 277–302. <https://doi.org/10.1007/s11214-008-9440-2>
- McPherron, R. L., Nakamura, R., Kokubun, S., Kamide, Y., Shiokawa, K., Yumoto, K., et al. (1997). Fields and flows at GEOTAIL during a moderate substorm. *Advances in Space Research*, 20, 923–931. [https://doi.org/10.1016/S0273-1177\(97\)00500-0](https://doi.org/10.1016/S0273-1177(97)00500-0)
- Mende, S. B., Harris, S. E., Frey, H. U., Angelopoulos, V., Russell, C. T., Donovan, E., et al. (2008). The THEMIS array of ground-based observatories for the study of auroral substorms. *Space Science Reviews*, 141, 357–387. <https://doi.org/10.1007/s11214-008-9380-x>
- Merkin, V. G., & Sitnov, M. I. (2016). Stability of magnetotail equilibria with a tailward B_z gradient. *Journal of Geophysical Research: Space Physics*, 121, 9411–9426. <https://doi.org/10.1002/2016JA023005>
- Nakamura, R., Baker, D. N., Yamamoto, T., Belian, R. D., Bering, E. A. III, Benbrook, J. R., & Theall, J. R. (1994). Particle and field signatures during pseudobreakup and major expansion onset. *Journal of Geophysical Research*, 99, 207–221. <https://doi.org/10.1029/93JA02207>
- Nakamura, R., Baumjohann, W., Klecker, B., Bogdanova, Y., Balogh, A., Rème, H., et al. (2002). Motion of the dipolarization front during a flow burst event observed by Cluster. *Geophysical Research Letters*, 29(20), 1942. <https://doi.org/10.1029/2002GL015763>
- Nakamura, R., Baumjohann, W., Schödel, R., Brittnacher, M., Sergeev, V. A., Kubyskhina, M., et al. (2001). Earthward flow bursts, auroral streamers, and small expansions. *Journal of Geophysical Research*, 106, 10,791–10,802. <https://doi.org/10.1029/2000JA000306>
- Nishimura, Y., Yang, J., Pritchett, P. L., Coroniti, F. V., Donovan, E. F., Lyons, L. R., et al. (2016). Statistical properties of substorm auroral onset beads/rays. *Journal of Geophysical Research: Space Physics*, 121, 8661–8676. <https://doi.org/10.1002/2016JA022801>

Acknowledgments

We acknowledge NASA contract NAS5-02099 for use of data from the THEMIS Mission and, specifically, for the use of FGM data supported through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302. For the GBO/ASIs, we acknowledge S. Mende and E. Donovan, NASA contract NAS5-02099, and the CSA for logistical support in fielding and data retrieval from the GBO stations. The THEMIS data were obtained freely from Space Sciences Laboratory—University of California, Berkeley (<ftp://themis.ssl.berkeley.edu/data/themis/>). The work of W. B., R. N., and E. V. P. was supported by the Austrian Science Fund (FWF): I 2016-N20 and I 3506-N27. The work of M. V. K. was supported by the Russian Science Foundation (RSF) grant 18-47-05001. The authors are grateful to V. Angelopoulos, M. I. Sitnov, F. Toffoletto, and R. A. Wolf for insightful discussions.

- Ohtani, S.-i. (1998). Earthward expansion of tail current disruption: Dual-satellite study. *Journal of Geophysical Research*, 103, 6815–6826. <https://doi.org/10.1029/98JA00013>
- Panov, E. V., Baumjohann, W., Wolf, R. A., Nakamura, R., Angelopoulos, V., Weygand, J. M., & Kubyshkina, M. V. (2016). Magnetotail energy dissipation during an auroral substorm. *Nature Physics*, 12, 1158–1163. <https://doi.org/10.1038/nphys3879>
- Panov, E. V., Nakamura, R., Baumjohann, W., Kubyshkina, M. G., Artemyev, A. V., Sergeev, V. A., et al. (2012). Kinetic ballooning/interchange instability in a bent plasma sheet. *Journal of Geophysical Research*, 117, A06228. <https://doi.org/10.1029/2011JA017496>
- Panov, E. V., & Pritchett, P. L. (2018a). Dawnward drifting interchange heads in the Earth's magnetotail. *Geophysical Research Letters*, 45, 8834–8843. <https://doi.org/10.1029/2018GL078482>
- Panov, E. V., & Pritchett, P. L. (2018b). Ion cyclotron waves rippling ballooning/interchange instability heads. *Journal of Geophysical Research: Space Physics*, 123, 8261–8274. <https://doi.org/10.1029/2018JA025603>
- Panov, E. V., Sergeev, V. A., Pritchett, P. L., Coroniti, F. V., Nakamura, R., Baumjohann, W., et al. (2012). Observations of kinetic ballooning/interchange instability signatures in the magnetotail. *Geophysical Research Letters*, 39, L08110. <https://doi.org/10.1029/2012GL051668>
- Partamies, N., Amm, O., Kauristie, K., Pulkkinen, T. I., & Tanskanen, E. (2003). A pseudo-breakup observation: Localized current wedge across the postmidnight auroral oval. *Journal of Geophysical Research*, 108(A1), 1020. <https://doi.org/10.1029/2002JA009276>
- Pritchett, P. L. (2015). Instability of current sheets with a localized accumulation of magnetic flux. *Physics of Plasmas*, 22(6), 062102. <https://doi.org/10.1063/1.4921666>
- Pritchett, P. L., & Coroniti, F. V. (1994). Convection and the formation of thin current sheets in the near-Earth plasma sheet. *Geophysical Research Letters*, 21, 1587–1590. <https://doi.org/10.1029/94GL01364>
- Pritchett, P. L., & Coroniti, F. V. (1995). Formation of thin current sheets during plasma sheet convection. *Journal of Geophysical Research*, 100, 23,551–23,566. <https://doi.org/10.1029/95JA02540>
- Pritchett, P. L., & Coroniti, F. V. (2010). A kinetic ballooning/interchange instability in the magnetotail. *Journal of Geophysical Research*, 115, A06301. <https://doi.org/10.1029/2009JA014752>
- Pritchett, P. L., & Coroniti, F. V. (2011). Plasma sheet disruption by interchange-generated flow intrusions. *Geophysical Research Letters*, 38, L10102. <https://doi.org/10.1029/2011GL047527>
- Pritchett, P. L., & Coroniti, F. V. (2013). Structure and consequences of the kinetic ballooning/interchange instability in the magnetotail. *Journal of Geophysical Research: Space Physics*, 118, 146–159. <https://doi.org/10.1029/2012JA018143>
- Pritchett, P. L., Coroniti, F. V., & Nishimura, Y. (2014). The kinetic ballooning/interchange instability as a source of dipolarization fronts and auroral streamers. *Journal of Geophysical Research: Space Physics*, 119, 4723–4739. <https://doi.org/10.1002/2014JA019890>
- Runov, A., Angelopoulos, V., Sitnov, M. I., Sergeev, V. A., Bonnell, J., McFadden, J. P., et al. (2009). THEMIS observations of an earthward-propagating dipolarization front. *Geophysical Research Letters*, 36, L14106. <https://doi.org/10.1029/2009GL038980>
- Schmid, D., Volwerk, M., Nakamura, R., Baumjohann, W., & Heyn, M. (2011). A statistical and event study of magnetotail dipolarization fronts. *Annales Geophysicae*, 29, 1537–1547. <https://doi.org/10.5194/angeo-29-1537-2011>
- Sergeev, V. A., Gordeev, E. I., Merkin, V. G., & Sitnov, M. I. (2018). Does a local B-minimum appear in the tail current sheet during a substorm growth phase? *Geophysical Research Letters*, 45, 2566–2573. <https://doi.org/10.1002/2018GL077183>
- Sergeev, V. A., Kubyshkina, M. V., Baumjohann, W., Nakamura, R., Amm, O., Pulkkinen, T., et al. (2005). Transition from substorm growth to substorm expansion phase as observed with a radial configuration of ISTP and Cluster spacecraft. *Annales Geophysicae*, 23, 2183–2198. <https://doi.org/10.5194/angeo-23-2183-2005>
- Sitnov, M. I., Birn, J., Ferdousi, B., Gordeev, E., Khotyaintsev, Y., Merkin, V. G., et al. (2019). Explosive magnetotail activity. *Space Science Reviews*, 215, 31. <https://doi.org/10.1007/s11214-019-0599-5>
- Sitnov, M. I., Buzulukova, N., Swisdak, M., Merkin, V. G., & Moore, T. E. (2013). Spontaneous formation of dipolarization fronts and reconnection onset in the magnetotail. *Geophysical Research Letters*, 40, 22–27. <https://doi.org/10.1029/2012GL054701>
- Sitnov, M. I., Merkin, V. G., Pritchett, P. L., & Swisdak, M. (2017). Distinctive features of internally driven magnetotail reconnection. *Geophysical Research Letters*, 44, 3028–3037. <https://doi.org/10.1002/2017GL072784>
- Sitnov, M. I., Merkin, V. G., Swisdak, M., Motoba, T., Buzulukova, N., Moore, T. E., et al. (2014). Magnetic reconnection, buoyancy, and flapping motions in magnetotail explosions. *Journal of Geophysical Research: Space Physics*, 119, 7151–7168. <https://doi.org/10.1002/2014JA020205>
- Sitnov, M. I., Swisdak, M., & Divin, A. V. (2009). Dipolarization fronts as a signature of transient reconnection in the magnetotail. *Journal of Geophysical Research*, 114, A04202. <https://doi.org/10.1029/2008JA013980>
- Weygand, J. M., Amm, O., Viljanen, A., Angelopoulos, V., Murr, D., Engebretson, M. J., et al. (2011). Application and validation of the spherical elementary currents systems technique for deriving ionospheric equivalent currents with the North American and Greenland ground magnetometer arrays. *Journal of Geophysical Research*, 116, A03305. <https://doi.org/10.1029/2010JA016177>