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Ionospheric convection signatures of tail fast flows during substorms and Poleward Boundary Intensifications (PBI)

Eftyhia Zesta,[1] Yong Shi,[2] E. Donovan,[3] E. Spanswick,[3] Larry R. Lyons,[2]
V. Angelopoulos,[4] J. P. McFadden,[5] C. W. Carlson,[5] Hans-Ulrich Auster,[6] S. Mende,[5]
M. A. McCready,[7] C. J. Heinselman,[7] E. Kendall,[7] and R. Doe[7]

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[1] Tail fast flows have been associated both with the onset of substorms and with auroral Poleward Boundary Intensifications (PBIs) that extend equatorward as streamers. We study here a series of bursts of fast tail flow that occurred on 5 March 2008 when four of the THEMIS probes were aligned in the tail from mid-tail to inner magnetosphere and were in good conjunction with the Sondrestrom Incoherent Scatter Radar. The series of burst are identified as two separate events. We find that the first event is associated with a small substorm onset, and the second with a PBI and then possibly another onset. The ionospheric flow signatures of the substorm and the PBI are distinctly different: the substorm onset is characterized by flow enhancement in the polar cap several minutes before onset and by sudden ionospheric flow reduction at onset, while the PBI is accompanied by a flow enhancement directed primarily equatorward and intruding from the polar cap into the plasma sheet. **Citation:** Zesta, E., et al. (2011), Ionospheric convection signatures of tail fast flows during substorms and Poleward Boundary Intensifications (PBI), *Geophys. Res. Lett.*, *38*, L08105, doi:10.1029/2011GL046758.

1. Introduction

[2] Transport in the tail plasma sheet is an essential component of global magnetospheric energy, mass and magnetic flux transfer, and is often organized in azimuthally localized bursts of earthward directed fast flows [e.g., *Baumjohann et al.*, 1990; *Angelopoulos et al.*, 1992]. Such flow channels can occur over the entire azimuthal width of the plasma sheet, during all levels of geomagnetic activity, and can be responsible for 60–100% of the measured earthward transport of mass, energy and magnetic flux, although they occur more frequently with higher AE.

[3] Several studies have shown both general [*Henderson et al.*, 1998; *Sergeev et al.*, 1999; *Sergeev*, 2004; *Lyons et al.*, 1999] and one-to-one [*Zesta et al.*, 2000, 2002, 2006; *Nakamura et al.*, 2001, 2005] associations of fast flow channels in the plasma sheet with roughly north-south aligned auroral forms, termed "streamers" [*Henderson et al.*, 1998; *Sergeev et al.*, 1999], and Poleward Boundary Intensifications (PBIs), which are transient auroral intensifications that initiate at the open-closed field boundary. Streamers generally extend equatorward from PBIs [*Lyons et al.*, 1999; *Zesta et al.*, 2000, 2002].

[4] Studies such as those mentioned above indicate that PBIs and streamers identify the footpoint of tail fast flow channels. A more limited number of studies [e.g., *Amm and Kauristie*, 2002; *Sergeev*, 2004; *Nakamura et al.*, 2005; *Kauristie et al.*, 2003] have linked the ionospheric current system of tail fast flows with PBIs and streamers. Study of the ionospheric convection associated with tail fast flows is even more limited. *de La Beaujardière et al.* [1994], *Grocott et al.* [2004], and *Nakamura et al.* [2005] found equatorward ionospheric flows associated with PBIs, while the latter two works also linked them to tail fast flows. There is good evidence of the association of tail fast flows and substorm onset [e.g., *Hesse and Birn*, 1991; *Haerendel*, 1992; *Shiokawa et al.*, 1998; *Nagai et al.*, 1998; *Voronkov*, 2005; *Angelopoulos et al.*, 2008; *Nishimura et al.*, 2010; *Lyons et al.*, 2010], although the cause and effect relationship is still under intense debate in the community. Comparison between tail fast flows and their related ionospheric flows observed in association with a PBI and with a substorm onset is thus of great interest and it is the main goal of the present paper.

[5] We use a conjunction of the Sondrestrom incoherent scatter radar (ISR) with the THEMIS probes [*Sibeck and Angelopoulos*, 2008] to investigate the ionospheric signatures of tail fast flows associated with PBIs and substorms. The ISR provides high-time resolution observations of the *F*- region convection flow, and direct measurements of ionospheric electron number density. We analyze an event having two consecutive activations on March 05, 2008, between 0155 and 0230 UT. We interpret the signatures as a small substorm onset followed by a PBI ~25 minutes later, with a possible second onset after the PBI.

2. Observations

[6] Figure 1a shows the THEMIS probe tail alignment at 0200 UT on Mar 5, 2008. Particle flux observations (not shown) confirm that four of the probes were inside the tail plasma sheet from 00 UT to past 06 UT. Probe P5 was very near Earth and is not used further. Figure 1b shows the ion velocity and magnetic field observations from the four probes. From top to bottom, we plot the three GSM com-

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[1] Air Force Research Laboratory, RVBXP, Hanscom AFB, Massachusetts, USA.

[2] Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA.

[3] Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada.

[4] Department of Earth and Space Sciences, University of California, Los Angeles, California, USA.

[5] Space Science Laboratory, University of California, Berkeley, California, USA.

[6] Technical University of Braunschweig, Brunswick, Germany.

[7] Center for Geospace Studies, SRI International, Menlo Park, California, USA.

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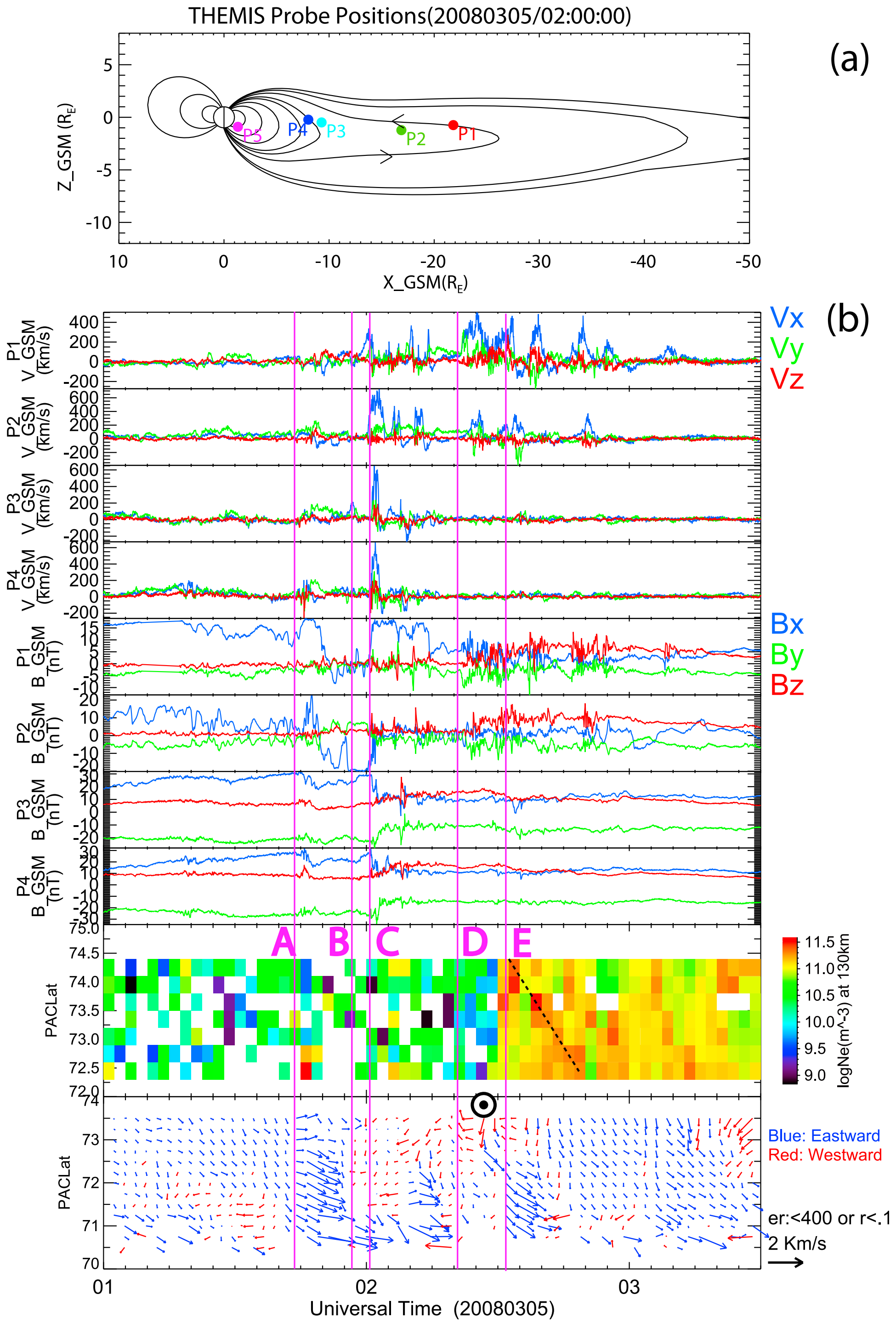

Figure 1. (a) Projection of the five THEMIS probes in X-Z (GSM) plane along with representative field lines at 02:00 UT on March 05, 2008 from the T89 model [*Tsyganenko*, 1989]. (b) Stack plots of the THEMIS observations of the tail plasma observations and of the Sondrestrom ISR on March 05, 2008. From top to bottom are three components of ion velocity and magnetic field in GSM coordinate observed by THEMIS P1, P2, P3, and P4, respectively. The two bottom panels show the ISR observations of electron density at 130 km and velocity vectors vs time and PACE latitude. The five vertical lines show key times during the two events.

ponents of the ion velocity and magnetic field from P1, P2, P3, and P4, respectively. The bottom two panels show the Sondrestrom radar observations discussed later.

[7] The five vertical lines mark key times A, B, C, D, and E. At time A, 0143 UT, substantial tail magnetic field perturbations were observed by the THEMIS probes and a significant flow enhancement is observed by the radar (Figure 1b, bottom), while ground magnetometers and the ASI (data not shown) at SNKQ observe magnetic perturbations and arc intensification, respectively. At time B, 0157 UT, the first fast flow burst is observed to initiate at P1 while the ionospheric flow at magnetic latitudes $\Lambda > 71^{o}$

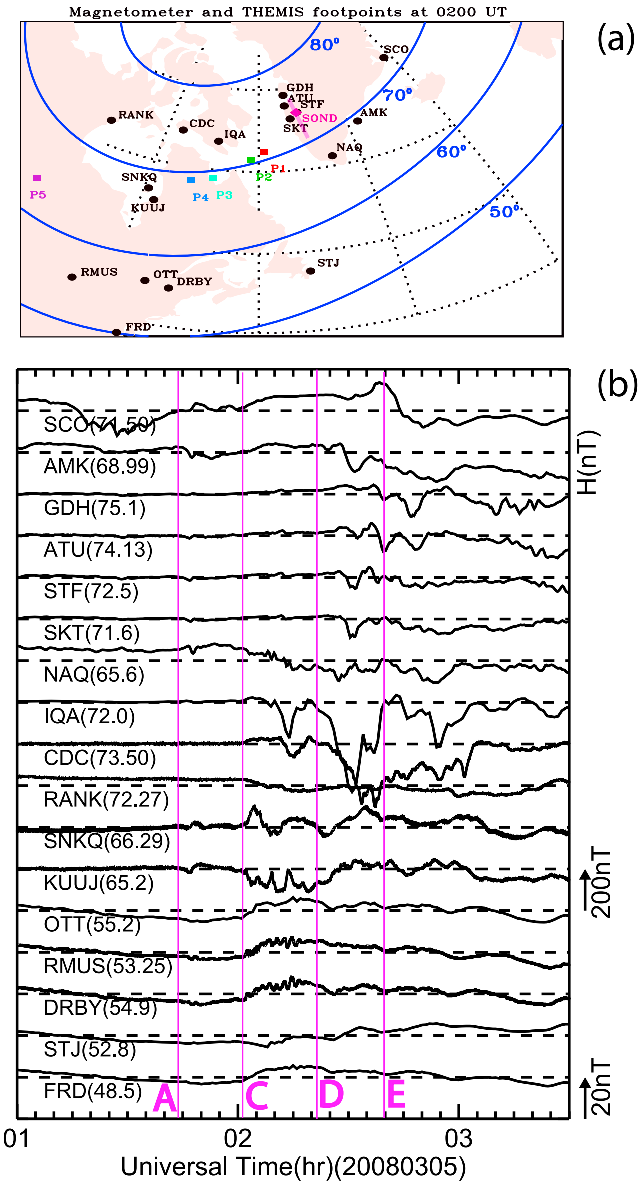

Figure 2. (a) Map of the footpoints of the five THEMIS probes in the ionosphere at 02:00 UT on March 05, 2008, indicated as colored circles. The Sondrestrom radar is shown as a magenta square, its scanning meridian along the coast of Greenland indicated with a light magenta bar. The magnetometers are indicated as black triangles. Black dashed lines: geographical latitude/longitude lines. Blue lines: constant corrected geomagnetic latitude lines from 50° to 80°. (b) Ground magnetometer observations during the time period of the substorm and the PBIs, along with the AU, AL, AE indices at the bottom. The four vertical lines correspond to key times during the substorm and PBI events.

(which is within the polar cap, based on the simultaneously measured E-region densities discussed later) significantly decreased 2 minutes earlier (Figure 1b, bottom). At time C, 0201 UT, the fast flow arrives at P4 and P3 in the inner magnetosphere at the same time as the auroral onset (Figure 3a). Time D, 0221 UT, is the onset of a series of fast flows at P1 that do not make it past P2 and are associated with a series of PBIs, and time E at ~0232 UT is that of possibly a second onset or another strong PBI. During the first event (times A, B, and C), fast flows are first observed within the polar cap, 19 minutes before substorm onset and then at THEMIS, initiating in the mid-tail ($-20\ R_E$) 4 minutes before onset, and subsequently penetrating into the inner magnetosphere ($-7\ R_E$). P3 and P4 observe clear dipolarizations in the inner magnetosphere, typical of a substorm onset, while P2 and P1 in the mid-tail only observe enhanced magnetic field fluctuations. During the second event (times D and E) fast flows are seen at P1 and much weaker at P2, accompanied by dipolarizations there, but do not penetrate into the inner magnetosphere. We show that the first fast flow event is associated with a small and localized substorm onset, while the second event is associated with a series of PBIs and possibly another onset near the end.

[8] Figure 2a shows the ionospheric footpoints of the probes P1, P2, P3, P4 and P5 at 0200 UT on March 5, 2008 as red, green, light blue, blue, and purple solid squares, respectively, along with ground stations used in this study. At the time, P1–P4 were within 1–2 hrs MLT of the Sondrestrom radar (a magenta diamond). Figure 2b shows ground magnetometer observations from 17 auroral and mid-latitude stations in North America and Greenland, locations being indicated in Figure 2a as solid black circles. High latitude stations are plotted in the upper panels, and mid-latitude stations in the lower panels using a different scale. Station codes are indicated below each trace with Λ for each station in parenthesis. The four vertical lines indicate times A, C, D, and E. We see small perturbations at all stations within 2 minutes of time A, when convection enhanced in the polar cap and in situ magnetic perturbations were observed in the tail. At ~0201 UT (time C, when the tail fast flow reaches inner magnetosphere), lower latitude stations observe the onset of a positive bay with superimposed Pi2 pulsations (e.g., DRBY and RMUS). Weak negative bays are seen at KUUJ, SNKQ, and RANK, the first two being at typical substorm onset Λ's, suggesting a localized substorm onset. Associated with the second fast flow event, starting at 0221 UT (time D), CDC and IQA, two of the highest latitude stations, observed strong perturbations that initiated just before D and peaked at ~0225 UT. These are significantly stronger than at any other station, but they are localized to only these two stations, indicating a strong localized current over them at the time. The high latitude stations over Greenland (SKT, STF, ATU, AMK) show a coherent smaller perturbation initiating at 0228 UT, which is consistent with the ground signatures of PBIs [e.g., *Lyons et al.*, 2002]. A new set of PBI-like perturbations initiates over Greenland just after 0235 UT. Weak positive bays are seen at OTT, STJ, and DRBY (with weak overriding Pi2s), at both 0225 UT and 0240 UT, near the local time of Sondrestrom, indicating narrow current wedge structures that have been suggested to be associated with PBIs [*Amm and Kauristie*, 2002]. This is the first direct report of mid-latitude positive bays associated with PBIs, although they were seen before in the event published by *Zesta et al.* [2006]. In summary, the ground magnetometer observations indicate a substorm onset at 0201 UT, a strong localized current over CDC and IQA that peaked at 0225, PBI-type perturbations over Greenland at 0225 UT, and a less clear signature over Greenland at ~0240 UT. The auroral observations shown below provide some clarification of this picture.

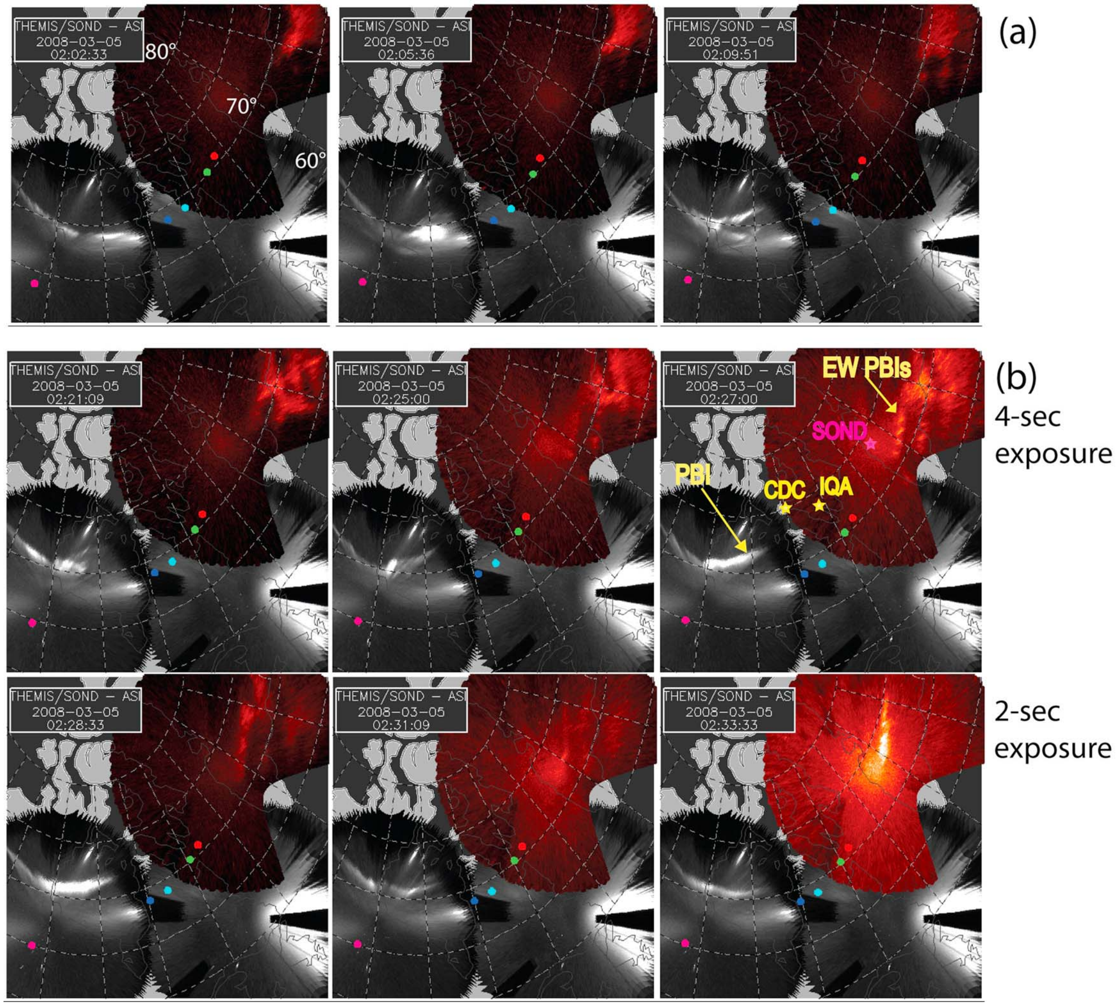

Figure 3. (a) Three representative merged ASI images, including 2 THEMIS ASIs and the Sondrestrom ASI, during the substorm onset around ~0200 UT. (b) Six merged images for the period of PBI onsets starting at ~0221 UT. The footpoints of the THEMIS probes are also plotted in the figures.

[9] Figure 3a shows three composite auroral mosaics from the THEMIS All Sky Imagers (ASIs) at GILL and SNKQ, and from the Sondrestrom ASI showing times just after onset (0202:33 UT) and during the development and propagation of the substorm surge (0205:36 UT and 0209:51 UT, after event C in Figure 1). Note that the THEMIS ASIs are white light cameras, while the Sondrestrom ASI observations are of 630nm emissions and are depicted in red. The footpoints of the THEMIS probes P1, P2, P3, P4, and P5, are shown in red, green, light blue, blue and purple, respectively. Geomagnetic latitude lines are marked in the first mosaic. The footpoints of P3 and P4 are the ones closest to the auroral onset, confirming that the fast flow and dipolarizaton signatures observed in situ by them are related to this substorm onset. During this localized onset and expansion no auroral activity is seen in the Sondrestrom ASI.

[10] Figure 3b shows six mosaics corresponding to the time period of the second set of fast flows, from 0221 to 0235 UT (event D in Figure 1). The top three mosaics include images from the Sondrestrom ASI at 4-sec exposure time. For the bottom three mosaics 2-sec exposure images were used, because the 4-sec exposures were saturated after ~0229 UT, due to enhanced aurora under an increasingly cloudy sky. At ~0221 UT, while weakening of the prior auroral surge can still be seen close to the footpoints of P3 and P4, a PBI structure appeared in over eastern Greenland and stretched equatorward. At 0225:00 UT, at least three distinct east-west (EW) extending PBI arcs can be distinguished over eastern Greenland, at the same time as the PBI-like perturbations initiated at the ground magnetometers (Figure 2b, time D). In the same mosaic a PBI begins to form just west of Baffin Island, along the pre-existing substorm surge, and it intensifies in the next mosaic of 0227:00 UT (identified there with an arrow). We believe this is the PBI that is responsible for the strong ground magnetometer perturbations in CDC and IQA. At the same time, the series of PBI arcs to the east have strengthened and expanded over Greenland. Flows at P1 and P2 could be related to the PBI near Baffin Island or those over Greenland, or both, given the location of the P1 footpoint. The PBIs over Greenland continue to strengthen and remain relatively stable in location until ~0230 UT. Note, that the two distinct arcs seen in the 0227:00 UT mosaic over Greenland are also evident in the previous mosaic but are very weak. So this is not a poleward expansion of a substorm, but rather the in situ intensification of poleward arcs, i.e. PBIs. Just after 0231 UT, under more cloudy conditions, the 2-sec

exposure images indicate a new intensification of an arc that starts in the prior PBI location but then moves poleward about 2°–3°. This intensification is associated with the ground magnetometer PBI-like perturbations that initiate after 0235 UT, both aurora and ground magnetometers persisting until ~0255 UT. It is not clear from the available observations whether this last intensification is another, stronger PBI, or a second onset. In situ THEMIS observations show fast flows and dipolarization at P1 (instance E), but no activity in the inner magnetosphere, although P3 and P4 might simply have missed the activity due to their location. On the other hand, the 2°–3° poleward expansion of this last intensification is not uncommon in strong PBIs either [*Zesta et al.*, 2006; *Liu et al.*, 2008]. The footpoints of P1 and P2 are close to Sondrestrom, implying that the fast flow and dipolarization signatures observed by them are closely related to the PBIs. The fast flows at times D and E are also associated with in situ plasma density decreases (not shown) at P1 and P2. The flow, dipolarization, and density decrease all start ~1 min earlier at P1 than at P2 making them consistent with the earthward propagating dipolarization fronts that have recently been reported [*Runov et al.*, 2009].

[11] We now look in more detail at how the ionospheric flows relate to the above signatures. The bottom two panels of Figure 1b show the ISR E-region electron number density at 130 km, and the F-region flow vector as a function of UT and Λ (covering 70.5°–73.5°). Flow vectors with an eastward component are plotted blue, and those with a westward component are plotted red, and midnight MLT is ~0200 UT. At the time, the Sondrestrom ISR was operating in a scan mode that allows the determination of the total ionospheric velocity vector with a 5-minute resolution, and of flow changes with a 2.5-minute resolution.

[12] At time A, at ~0143 UT, there was strong enhancement of eastward flow at all latitudes, while *E*-region electron densities were low as expected from being within the polar cap. This is confirmed by a DMSP pass near the radar MLT identifying the separatrix (open-closed field line boundary) at Λ ~ 70°–71, i.e. near the lowest Λ measurements. Associated with this flow enhancement in the polar cap, magnetic field perturbations are seen at all THEMIS probes (Figure 1b), and at auroral and mid-latitude ground magnetometers (Figure 2b), indicating association between the polar cap flow enhancement and magnetotail activity. No solar wind signature is seen associated with this flow enhancement.

[13] The ionospheric flow decreased dramatically near time B, at 0152 UT, at $\Lambda > 71°$, and soon became primarily westward. The flow at $\Lambda < 71°$ remained strongly eastward creating a strong shear at ~71° from 0157–0208 UT. When the PBI occurred, at 0225 UT, the flow (which had weakened at all latitudes just a few minutes before) enhanced again and turned strongly equatorward at $\Lambda > 72.5°$. More specifically, between 0220 UT and 0230 UT and at $\Lambda > 73°$ the flow vectors show a clear counter-clockwise rotation indicating an upward FAC moving into the field of view of the radar from the east, consistent with the intensification of the PBI arcs seen in the 2nd and 3rd mosaics of Figure 3b. Immediately after, a strong localized electron density enhancement is seen, likely the result of the auroral precipitation associated with the FAC. The equatorward flow enhancement then quickly moved to lower latitudes, followed by the electron density enhancement (the latter's path indicated with a dashed line in Figure 1). The flow is seen first within the polar cap ~2–5 min before the auroral activity moved to the radar meridian.

3. Discussion and Conclusions

[14] In the double event analyzed here, we found that tail fast flow signatures associated with a substorm and a PBI event are distinct, as are the ionospheric flow signatures associated with each event. In the case of the substorm onset, fast flows were first observed within the polar cap, 19 minutes before onset (with associated disturbances in the tail and aurora ~2 minute later), and then were observed first in mid-tail, at $-20\ R_E$, 4 min prior to onset. They then moved progressively closer to the Earth at $-8\ R_E$. Prolonged dipolarization only appeared in the inner magnetosphere, while the mid-tail probes observed only magnetic field fluctuations. When the fast earthward flow was first observed at mid-tail the ISR observed significant flow reduction at the highest latitudes, but persisted at the lowest latitudes of its field of view. The auroral onset and magnetospheric dipolarization do not happen until the tail fast flow reaches the inner magnetosphere. This event progression is in accord with the substorm sequence described by *Angelopoulos et al.* [2008] and by *Nishimura et al.* [2010], and the radar observations of *Lyons et al.* [2010].

[15] The fast flows associated with the PBI have different characteristics. The second fast flow event is first observed at $-20\ R_E$ and then at $-16\ R_E$ much decelerated, accompanied by dipolarizations there, however no fast flow or dipolarization is observed in the inner magnetosphere consistent with the *Nakamura et al.* [2001] results that tail fast flows associated with streamers (PBIs) occur tailward of $-16\ R_E$. The PBI is observed in the Sondrestrom ISR and ASIs at the same time, while the ionospheric flow signature is an enhancement with a dominant equatorward component, showing intrusion from the polar cap into the plasma sheet and consistent with an upward FAC, which couples the distant tail fast flow to an auroral PBI. We also found that the tail signatures of the PBIs are consistent with propagating dipolarization fronts. We identify 3 additional key differences between the substorm onset and the PBI events: (a)the substorm tail flows penetrate to the inner magnetosphere, while the PBI fast flows attenuate before $-16\ R_E$, (b) substorm onset is at a lower latitude expanding poleward and westward, while the PBIs are in situ intensification of poleward arcs, and (c) the substorm has longer-lasting, strong mid-latitude bays with strong Pi2s, while the PBIs have significantly weaker, more localized mid-latitude bays with weaker Pi2's indicating that the substorm is associated with a stronger inner magnetosphere current wedge, while the PBI is associated with a weaker, outer magnetosphere, more localized current wedge.

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V. Angelopoulos, Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095, USA.

H.-U. Auster, Technical University of Braunschweig, D-38106 Braunschweig, Germany.

C. W. Carlson, J. P. McFadden, and S. Mende, Space Science Laboratory, University of California, Berkeley, CA 94720, USA.

R. Doe, C. J. Heinselman, E. Kendall, and M. A. McCready, Center for Geospace Studies, SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025, USA.

E. Donovan and E. Spanswick, Department of Physics and Astronomy, University of Calgary, Calgary, AB T0L 2C0, Canada.

L. R. Lyons and Y. Shi, Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095, USA.

E. Zesta, Air Force Research Laboratory, RVBXP, 29 Randolph Rd., Hanscom AFB, MA 01731, USA. (ftyhia.Zesta@hanscom.af.mil)