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PFISR observations of strong azimuthal flow bursts in the ionosphere and their relation to nightside aurora

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ABSTRACT

Flow bursts within the ionosphere are the ionospheric signatures of flow bursts in the plasma sheet and have been associated with poleward boundary intensifications (PBIs). Some PBIs extend equatorward from the polar cap boundary, where they can be roughly divided into north-south-aligned and east-west-aligned structures. In this paper, we present two flow burst events observed by the new Poker Flat Advanced Modular Incoherent Scatter Radar (PFISR) in the pre-midnight auroral zone on 28 April 2007, one towards the west and the other towards the east. In both cases, enhanced flows lasted for about 8-10 min with peak velocities exceeding 1500 m/s. The concurrently measured electron density showed that the flow bursts occurred in low conductivity regions. However, near the poleward (equatorward) edge of the westward (eastward) flow burst, strong electron density enhancements were observed in the E region, indicating the presence of discrete auroral arcs. Auroral images from the Polar spacecraft were available at the time of the eastward flow burst and they indicate that this burst was associated with an east-west-aligned auroral structure that connected at later MLT to a north-south structure. In addition, simultaneous precipitating particle energy spectrum measured by the the Defense Meteorological Satellites Program (DMSP) F13 satellite reveals that this auroral structure resulted from mono-energetic electron precipitation associated with a significant field-aligned potential drop. These observations show direct evidence of the relationship between flow bursts, field-aligned currents and auroral intensifications, and suggest that eastward/westward flow bursts are associated with east-west-oriented PBI structures that have extended well within the plasma sheet. This is in contrast to the equatorward-directed flow that has been previously inferred for PBIs near the polar cap boundary and for north-south auroral structures. This paper illustrates the use of the PFISR radar for studying the magnetosphere-ionosphere coupling of flow bursts.

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1. Introduction

Bursts of enhanced plasma flow have been observed within the ionosphere using incoherent scatter radars (ISRs) (e.g., de la Beaujardière et al., 1994) and coherent scatter radars (e.g., Sergeev et al., 1990; Walker et al., 1998; Grocott et al., 2004) under different interplanetary conditions. These flow bursts have a peak speed of ~500–1000 m/s, and their typically observed duration in the ionosphere is ~10–20 min. The direction of a flow burst is mainly equatorward near the open-closed field line boundary (OCB), indicating localized regions of enhanced reconnection across the boundary (de la Beaujardière et al., 1994; Sergeev et al., 1990). The magnetospheric counterpart of an ionospheric flow burst is a transient burst of enhanced flows (structured flows seen for several minutes and having peak velocity $|V_X| \ge 400 \text{ km/s}$),

which are now believed to be an important means of plasma transport in the magnetotail (e.g., Baumjohann et al., 1990; Angelopoulos et al., 1992).

These flow bursts are associated with auroral enhancements near the polar cap boundary, which are known as poleward boundary intensifications or PBIs (de la Beaujardière et al., 1994; Kauristie et al., 1996; Yeoman and Lühr, 1997; Lyons et al., 1999; Zesta et al., 2000). PBIs are very common, occurring during all levels of geomagnetic activity (Lyons et al., 1998). The connection between flow bursts and PBIs arises because the flow bursts, which are quite localized in longitude (Angelopoulos et al., 1994, 1996), often give rise to a convergence of horizontal ionospheric current that supports an upward field-aligned current (e.g., Kauristie et al., 2003) which is sufficiently intense that a magnetic field-aligned potential drop is required, resulting in the acceleration of electrons downward towards the ionosphere and to auroral brightening.

PBIs have an auroral signature that can often be seen to move equatorward from the polar cap boundary. At times, the auroral

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region can extend a significant distance throughout the nightside plasma sheet, forming what are known as north-south auroral structures (also called auroral "streamers"). These north-south auroral structures have been associated with earthward flow bursts in the plasma sheet (Henderson et al., 1998; Sergeev et al., 1999; Kauristie et al., 2003). Zesta et al. (2000) showed a direct one-to-one correlation between five distinct north-south auroral structures and five equally distinct flow bursts in the tail, and Sergeev et al. (2000) also directly associated an auroral streamer with a flow burst in the tail.

Recently. PBIs have been found to extend equatorward from the OCB as either north-south structures or east-west arcs that mostly propagate equatorward (Zesta et al., 2002, 2006). The east-west events occur mostly in the dusk and pre-midnight sector, whereas the north-south events frequently occur around local midnight. To date, very little is known about the relationship between flow bursts and equatorward-moving east-west-oriented PBIs or the differences and similarities between the flows for these structures and those for north-south-oriented structures. Senior et al. (2002) reported bursts of enhanced flow directed azimuthally towards the dayside within the evening-side ionosphere, and they suggested the possibility that they may be associated with equatorward-directed flows observed near midnight. Evidence that an individual nightside equatorwarddirected flow burst was diverted towards the sunward direction within the inner plasma sheet was presented by Kauristie et al. (2003). It seems plausible, if these flow bursts are sufficiently localized in latitude, that they could be associated with east-westoriented PBIs.

The new Poker Flat Advanced Modular Incoherent Scatter Radar (PFISR), which looks poleward from its location at ~ 65.4° geomagnetic latitude, is often within the auroral oval. Its measurements of plasma velocity, electron density, ion and electron temperature, together with auroral imaging provide an opportunity to study the dynamics of convection flows in the auroral zone and their connection with auroral features. In particular, since the north–south and east–west-oriented PBIs reported by Zesta et al. (2000, 2002, 2006) can extend equatorward into the PFISR field-of-view, PFISR provides an excellent opportunity to evaluate the relationships between flow bursts and different types of PBIs.

In this paper, we demonstrate the use of PFISR observations for evaluating the relationships between the flow bursts and PBIs for two flow burst events observed by PFISR in the pre-midnight auroral zone on 28 April 2007. In the following section, we present data measured by multiple instruments, including PFISR, the Polar spacecraft, and a DMSP satellite. It is shown that the direction of the enhanced flows in one case was mainly westward and perhaps connected to earthwardflowing plasma as suggested by Kauristie et al. (2003). In the other case, the flows were eastward. The spatial relationship between the flow bursts and the aurora examined is found to be different for the two cases, but consistent with expectations based on the requirement for ionospheric current continuity. By combining observations together, we show direct evidence that the second flow burst was likely associated with an upward field-aligned current, the east-west portion of a PBI, and field-aligned electron energization. In the final section, we summarize the observational characteristics of the flow burst events and discuss their implications for the magnetosphere-ionosphere coupling processes.

2. Observations

2.1. IMF and solar wind conditions

Fig. 1 shows the solar wind and interplanetary magnetic field (IMF) conditions observed by the ACE spacecraft on 28 April 2007

from 0700 to 1530 UT (universal time) during the radar operation period, in GSM coordinates, propagated to 17 Re upstream of the magnetosphere using the Weimer minimum variance technique (Weimer et al., 2003). The original location of ACE was ~(246, -7, -20) Re, close to the Earth–Sun line. As illustrated in Fig. 1, the solar wind velocity was high at about 600 km/s and remained very steady during this period. In the meantime, the solar wind dynamic pressure had no major changes. In contrast, rapid and large-amplitude fluctuations were present in the IMF B_y and B_z , which is a well-known characteristic of solar wind high-speed streams. The IMF B_y , although highly variable, remained negative for 8 h. Significant auroral activity is expected to occur under such interplanetary conditions.

2.2. Radar observations

Since March of 2007, PFISR has been operating for 7-8 night time hours centered on MLT midnight (~1115 UT) several days a month in support of global convection measurement in the highlatitude ionosphere; 28 April 2007 is one interval for which radar measurements are available. On this day, PFISR was running in a normal 10-beam mode. The configuration of the radar beams is displayed in Fig. 2, in AACGM coordinates, with beams 1-3 pointing to the northwest, beams 4-6 to the northeast, beams 7-9 directly to the north, and beam 10 up along the magnetic field. Different beams are color-coded for clarification. As can be seen, the radar field-of-view covers about 6° in longitude and 3° in latitude. This experimental configuration supports simultaneous line-of-sight velocity measurement in multiple directions, which can provide reliable convection velocity vector measurement even when velocities vary rapidly (on time scales of minutes). During these experiments, two types of pulses were transmitted, a long pulse and an alternating code pulse. The former is designed for the F-region measurements and the latter for the E region. The alternating code measurements provide much higher spatial (range) resolution than that of the long pulse in the E region. More information about the radar transmission schemes and methodology of the velocity vector calculations (using beams 1-3 and 4-6) can be found in Heinselman and Nicolls (2008).

Fig. 3a, from bottom to top, shows PFISR observations of the plasma convection flow vector, its magnitude, and its direction as a function of UT and magnetic latitude. The data are shown with 4 min temporal resolution and the velocity vectors are binned by 0.25° geomagnetic latitude. Both magnitude and direction of the flow vectors are color-coded according to the color bars on the right. The bottom panel shows that, within the radar field-of-view, the flows were predominantly eastward after ~22 MLT (0915 UT), consistent with the enlarged dawn convection cell expected for IMF B_y negative conditions (e.g., Reiff and Burch, 1985). The flow magnitude shown in the middle panel, on the other hand, varied considerably throughout the radar run, which is at least in part due to the large-amplitude variations in the IMF.

Fig. 3b displays a zoom-in of the plasma convection during the time period from 0750 to 0850 UT, in the same format as Fig. 3a, but with 1 min temporal resolution. Both flow burst events under investigation can be seen here, as identified by magenta arrows. Based on Polar spacecraft auroral images, a substorm onset occurred at 09:15:19 UT. It is possible that the second flow burst is associated with the IMF southward turning at ~0830 UT, which initiated the growth phase of the substorm. The first flow burst occurred near the equatorial boundary of the radar field-of-view as the equatorward portion of a horizontal flow shear. The flow began to increase at ~0804 UT and persisted for about 8 min. There is evidence that this flow burst was connected with an enhancement in more equatorward-directed flows that extended



Fig. 1. The solar wind and interplanetary magnetic field (IMF) measurements from 0700 to 1530 UT on 28 April 2007 observed by the ACE spacecraft in GSM coordinates. They are propagated to 17 Re upstream of the Earth's magnetosphere using the Weimer minimum variance technique. Two magenta lines indicate the beginning of the two flow bursts.

from higher latitudes and were observed a few minutes later, similar to what Kauristie et al. (2003) reported. The second flow burst, which occurred between $\sim 67^{\circ}$ and 69° magnetic latitude, started to enhance at ~0828UT and lasted for about 10 min. During both flow bursts, the magnitude of the flow velocity peaked at a value in excess of 1500 m/s, corresponding to a perpendicular electric field of \sim 75 mV/m. The durations of the two flow bursts and the peak velocity are similar to previous observations (Sergeev et al., 1990; Senior et al., 2002). The direction of the first flow burst was in the westward direction and is probably a part of the return flows of the dusk convection cell. The strong velocity shear indicates converging electric fields near the center of the shear and poleward of the enhanced flow channel. The Pedersen currents associated with these electric fields are expected to feed an upward field-aligned current flowing out from the center of the shear at $\sim 67^{\circ}$ latitude in order to satisfy current continuity in the ionosphere. In contrast, the second flow burst was mainly in the eastward direction, so that an upward filed-aligned current is expected to occur at the equatorward edge of the enhanced flows where flow velocity gradients peaked.

Another useful ionospheric parameter that can be measured by PFISR is the electron density along the beam-look direction. Fig. 4, from top to bottom, displays the electron density (panels on the left) along with the line-of-sight ion velocity (panels on the right) as a function of altitude, which is a function of magnetic latitude, and UT from the long pulse measurements of the three northeastlooking beams 4-6. The temporal variation of the line-of-sight velocities measured by the northwest-looking beams 1-3 are very similar to beams 4–6 but with the opposite sign. Blue line-of-sight velocities are towards the radar and the yellow and red ones are away from the radar. The spatial resolution in altitude of the long pulse measurement is about 33 km and the temporal resolution is 1 min in this case. For the first case, beam 4 at the lowest latitude and with a high elevation angle clearly captured the flow enhancement, which is highlighted by a circle. Dark blue within the circle indicates strong flows towards the radar. However, nearly no flow enhancement was observed by the four central beams (not shown), suggesting the true flow vectors were in the westward direction, as shown in Fig. 3b. The electron density measured by beam 4, also highlighted by a circle, shows a substantial decrease below $\sim 250 \, \text{km}$ in the same region as the



Fig. 2. (a) PFISR 10-beam mode configuration in geomagnetic coordinates. (b) PFISR 10-beam mode configuration as a function of magnetic latitude and altitude.

enhanced flows, indicating that the flow enhancement occurred in a region of low auroral electron precipitation and of low ionospheric conductivity. At the same time, beam 6 at the highest latitude (lowest elevation angle) observed a strong E-region electron density increase at a latitude $\sim 1^{\circ}$ poleward of the strongest flow enhancement, also highlighted by a circle.

Unlike the first flow burst, the second flow enhancement covered a wider latitudinal range within the radar field-of-view and thus was clearly observed by all the three beams. A square is shown to indicate the flow enhancement in the flow panel for beam 6. Yellow/red line-of-sight velocities plus the weak flows measured by the central beams (not shown) indicate that the true flows were primarily in the eastward direction. Similar to the first case, the electron density also decreased in the flow-enhanced region, but the density increased just equatorward of the enhanced flows. The region of density decrease within the flow enhancement and density increase equatorward of the enhanced flows is marked by a square in the beam 6 density panel. The density decrease within the flow enhancement was seen at \sim 200–250 km. While there are no measurements at lower altitudes within the latitude range of the flow enhancement, it is reasonable to presume that the decrease extended to lower altitudes within the E region as was observed for the first flow burst. The more equatorward density increase, on the other hand, was observed at $\sim 100-200$ km. The relationship seen here between the ionospheric fast flows and the low electron density (thus low conductance) is similar to that of an evening-sector auroral arc observed by EISCAT (Aikio et al., 1993).

In both of our cases, the duration of flow enhancement and of E-region electron density increase is approximately the same. It is

also worth mentioning that, concurrent with the flow enhancement, the ion temperature increased dramatically (not shown) and that it even exceeded the electron temperature at some locations. This increase is likely to be a result of frictional heating.

The details of E-region electron density enhancements can be better revealed by the alternating code measurements with a spatial resolution of ~8.2 km in altitude, as shown in Figs. 5a and b, for the first and second events, respectively. Both plots show six panels of electron density measurements from the four central beams as a function of altitude and magnetic latitude. These plots display electron density measurement approximately in the same meridional plane. The beginning and ending UT is shown on the top of each panel. In Fig. 5a, the electron density at $\sim 67^{\circ}$ latitude, measured by the beam with the lowest elevation angle, dramatically increased by a factor of 3-6 during the flowenhanced period. This increase peaked at ~140 km, corresponding to precipitating electrons with energy \sim 1 keV (Rees, 1963), and indicating a discrete auroral arc. In addition, as revealed by the second and last panels, the initiation and ending of the density increase was coincident with that of the flow burst. Similarly, in Fig. 5b, we can see that the electron density increased when flows were enhanced and decreased when the enhancement ended. In this case, the electron density increase peaked at a lower altitude of ~110 km and near 66.7° latitude, indicating harder electron precipitation with energy ~5 keV (Rees, 1963). In both cases, the latitudinal location of the electron density increase is consistent with our expectation of the location of an upward field-aligned current based on the flow measurements.

2.3. Polar UVI observations

During the second period under investigation, auroral images were captured by the UVI camera onboard the Polar spacecraft over the southern auroral oval. Fig. 6 shows the number of photons per unit area per second measured by Polar at 08:35:27 and 08:36:40 UT in the dusk to midnight sector, in geomagnetic coordinates. A significant auroral arc can be seen in Fig. 6, which covered about 2 h in MLT, and between -65° and -71° magnetic latitude. Morphologically, it was composed of two parts, an east-west structure at lower latitude (-66-67°) extending from \sim 20 to 22 MLT and a brighter "north-south" structure at higher latitude covering about $4-5^{\circ}$ in latitude near ~ 22 MLT. We call this a "north-south" structure in analogy to the term being used when such structures are observed in the northern hemisphere. These two structures connected with each other near 22 MLT. A mapping of the PFISR radar field-of-view in the F region, represented by three plus signs, using the Tsyganenko 96 model (Tsyganenko, 1995, 1996) places the east-west auroral brightening well within the PFISR field-of-view. The enhanced flows were mapped to just equatorward of the two plus signs at high latitude and poleward of the peak of the auroral luminosity. This observation is consistent with our expectation based on PFISR measurements that an upward field-aligned current exists near the equatorward edge of the flow burst and demonstrates the relation between the eastward flow bursts and nightside aurora. Images after 08:36:40 UT show that both auroral structures slowly moved about 1–2° equatorward and the "north-south" structure gradually embedded itself into the east-west one. In fact, as shown in Fig. 1, the IMF B_z turned southward at ~0830 UT and remained relatively steady for about half an hour. The auroral equatorward motion could be a signature of polar cap expansion as a result of reconnection in the tail associated with this southward turning.



Fig. 3. (a) Overview of nightside flow velocities measured by PFISR from 0735 to 1530 UT on 28 April 2007. From bottom to top, the plot displays flow vector, its magnitude, and its direction as a function of UT and magnetic latitude. The temporal resolution is \sim 4 min. In the bottom panel, the red and blue vectors denote westward and eastward drifts, respectively. The scale is given in the lower right corner by an arrow representing 1500 m/s. In the top panel, the directions are zero for poleward flow in the meridianal plane and increase (decrease) clockwise (counterclockwise). (b) A zoom-in of flow velocities from 0750 to 0850 UT in the same format as (a), but with \sim 1 min temporal resolution. Each flow burst event is indicated by a magenta arrow.

2.4. DMSP observations

During this period, the Defense Meteorological Satellites Program (DMSP) F13 satellite moved equatorward across the auroral brightening region seen by Polar. The red square in each panel of Fig. 6 represents the footprint of the DMSP F13 spacecraft at the specified time calculated using the Tsyganenko 96 model. The satellite first hit the edge of the "north–south" structure at 08:35:20 UT and then passed through the east–west auroral structure between 08:36:40 and 08:37:54 UT. Fig. 7 displays the 30 eV–30 keV differential energy flux of precipitating electrons (top) and ions (bottom) measured by the precipitating particle spectrometer SSJ/4 onboard DMSP F13 as a function of UT, magnetic latitude, and MLT. Note that the ion energy scale is reversed. As evident in the top panel, the satellite detected the poleward boundary of the auroral oval (OCB) at 08:32:20 UT, characterized by soft electron precipitation and located at -75.5° magnetic latitude at 2350 MLT. At lower latitudes, two significant inverted-V arcs, pointed by arrows, were seen adjacent to each other and were bounded by narrow broader band auroral precipitation regions that have been associated with Alfvénic electron energization (Mende et al., 2003 and reference therein). It seems that the first inverted-V arc was associated with the "north–south" structure and the second one with the east–west



Fig. 4. Electron density N_e (panels on the left) and line-of-sight velocity V_{los} (panels on the right) as a function of altitude/magnetic latitude and UT from long pulse measurements of the northeast-looking beams 4–6. Blue line-of-sight velocities are towards the radar and the yellow and red ones are away from the radar. Circles highlight the flow and corresponding electron density changes for the first flow burst event, while squares highlight those for the second event.

structure. In both cases, the precipitating electron distribution peaked at about 4–6 keV. These precipitating electrons can penetrate to altitudes between 130 and 100 km (Rees, 1963), which is consistent with the PFISR observations shown in Figs. 4 and 5 for the east–west structure. These mono-energetic electrons were clearly accelerated by a potential drop along the field line as required for current continuity. Therefore, these DMSP observations show quite clearly the upward field-aligned current and auroral electron energization from the converging Peterson currents, as inferred from the PFISR observations of the flow burst. As marked by a horizontal magenta arrow, a narrow channel with weak electron precipitation between the two inverted-V arcs can be seen, which may be a signature of a depleted flux tube region within the plasma sheet associated with the flow burst.

3. Discussion and conclusions

Previous analyses have shown that equatorward flow bursts are associated with PBIs observed near the polar cap boundary and with auroral structures extending in approximately the north-south direction equatorward from the polar cap boundary. PFISR allows us to study the characteristics of flow bursts and their association with auroral structures within the central plasma sheet well equatorward of the polar cap boundary. In this initial study, we have investigated two ionospheric flow burst events observed by PFISR in the pre-midnight sector on 28 April 2007. In both cases, the enhanced flows lasted for about 8-10 min with peak velocities in excess of 1500 m/s. This duration is similar to the average duration of bursty flows in the plasma sheet as expected for the ionospheric manifestations of bursty flows observed in situ within the plasma sheet. The latitudinal width of the second flow burst was narrow, only $\sim 2^{\circ}$, while that of the first burst could not be determined because of the limited radar field-of-view. The directions of the flows were westward for the first case and eastward for the second one. Such westward flow bursts have been observed by the SuperDARN radars in nearly the same region but during quiet times (Senior et al., 2002). The different interplanetary conditions for our case and for theirs suggest that azimuthal flow bursts can occur at a wide range of geomagnetic activity levels, similar to PBIs (Lyons et al., 1998).

Concurrent electron density decreases and ion temperature increases in the same region as the flow enhancements were measured by PFISR. The former reveals that the flow enhancements occurred within low conductivity regions in the ionosphere. Whether this phenomenon is common for flow bursts needs further analysis. But if it is common, it would reflect important aspects of the bursty flows deep within the plasma



Fig. 5. (a) Electron density as a function of altitude and magnetic latitude from alternating code measurements of the four central beams 7–10 for the first flow burst event. The starting and ending time are indicated at the top of each panel. (b) The same format as (a), but for the second flow burst event.

sheet. A possibility would be that the plasma sheet density within flow bursts is low, as would be expected if flow bursts are associated with entropy-reduced flux tubes, as suggested by Chen and Wolf (1993). Simultaneous E-region electron density increases were observed at the edge of the flow bursts where converging Pedersen currents are expected, as has also been seen in the radar observations of Aikio et al. (1993). The altitude profile of the E-region enhancements indicates >1 keV electron precipitation and thus the existence of discrete auroral arcs. For the second event, auroral images observed by Polar and *in situ* precipitating particle spectrum measured by the DMSP F13 satellite were available and they observed a significant inverted-V arc resulting from 4 to 6 keV mono-energetic electron precipitation.

The Polar image for the second event showed an equatorwardmoving east-west-oriented structure, consistent with the results reported by Zesta et al. (2006) for PBI auroral structures at evening MLTs. Observations presented in this paper give direct evidence for the driving of converging Pedersen currents by the flow burst, leading to field-aligned currents and the equatorwarddrifting east–west auroral intensification. Thus, this event gives some initial evidence that eastward or westward flow bursts are related to east–west-aligned auroral forms, while more equatorward flows are associated with more north–south-aligned auroral structures.

It is interesting that although the latitudinal locations of the upward filed-aligned current were similar in both cases and their local time difference was small, only 0.5 MLT, the flow bursts were westward and eastward, respectively. This raises a very important question of the direction of the corresponding bursty flows in the plasma sheet. More specifically, whether there is significant dawnward or duskward component of these



Fig. 6. Auroral images observed by the UVI camera onboard the Polar spacecraft in the dusk to midnight sector at 08:35:27 and 08:36:40 UT, respectively. In each plot, red square represents the footprint of the DMSP F13 satellite at the specified time, and three orange plus signs outline the PFISR F-region field-of-view mapped using the Tsyganenko 96 model.



Fig. 7. DMSP observation of 30 eV-30 keV precipitating electrons (top) and ions (bottom) differential energy fluxes from 0831 to 0839 UT. Note that the ion energy is reversed. The open-closed field line boundary (OCB) is indicated by a white dotted line. The horizontal magenta arrow points to the precipitation region from a depleted flux tube.

earthward burst flows. Zesta et al. (2006) approached this problem using the Tsyganenko 96 model and have shown that the equatorial projection of both east-west and north-south structures tend to be radially aligned. If this is the case, then the direction of the ionospheric flow burst, whether it is azimuthal or meridional, could be a local time effect. If this is not the case, i.e., azimuthal flow bursts in the ionosphere are related with bursty flows with significant dawnward or duskward component near the equator, then the question would arise of what causes these dawnward or duskward flows? One possible explanation is that within the short 20 min gap between the first and second events, the radar moved from the region of return flow within the dusk convection cell to that of the dawn convection cell, and the flow bursts were flow enhancements superimposed on the background convection flows. In order to fully solve this problem, conjugate measurements in the plasma sheet and the ionosphere would be required. A good example would be conjugate observations of the THEMIS multi-spacecraft and the PFISR radar.

Since bursty flows in the plasma sheet are important for plasma, momentum, and energy transport in the magnetotail, the ionospheric flow bursts, as a mirror image of this process, are crucial to understanding these transport processes. The observations presented here have illustrated the use and importance of the PFISR radar for this type of study.

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