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Coordinated SuperDARN THEMIS ASI observations of mesoscale flow bursts associated with auroral streamers

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[1] Nightside auroral zone localized flow channels, typically associated with auroral poleward boundary intensifications and streamers, are an important component of high-latitude ionospheric plasma dynamics. We investigate the structure of these flow channels using two-dimensional line-of-sight flow observations from the Super Dual Auroral Radar Network (SuperDARN) radars and auroral images from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) ground-based all-sky imager (ASI) array. Radar echoes captured <~500 km horizontal distance from the radars were mainly used to detect small-scale flow structures that would otherwise be missed or poorly resolved in long-range radar echoes. After identifying 135 auroral streamers in the ASI images at close-radar capture locations, we examined the associated ionospheric flow data in the radar echoes. Flow bursts and streamers are invariably correlated in all events. The flow bursts are often directed equatorward and appear simultaneously with the streamers. Equatorward flows are located just to the east of the streamers. Less frequently (~10% of the time), a poleward flow enhancement was detected even when a streamer propagated equatorward, the poleward flow enhancement being located to the west of the auroral streamer, or to the east of the equatorward flow enhancement, consistently with the spatial relationship between flow shear and upward field-aligned currents in plasma sheet flow bursts. The azimuthal width of the flow channel is, on average, ~75 km, and the azimuthal offset of the equatorward flow channel relative to the auroral streamer is ~57 km eastward. This study demonstrates the capability of radar-imager pairs for identifying the 2-D structure of localized flows associated with plasma sheet flow bursts.

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1. Introduction

[2] Bursts of earthward flows in the plasma sheet are fundamental to the plasma transport in the magnetotail. Satellites in the plasma sheet frequently detect high-speed flows or bursty bulk flows (BBF) with a predominantly earthward propagation [e.g., *Angelopoulos et al*., 1992, 1994; *Baumjohann*, 1993]. Plasma sheet flow bursts have small cross-tail scale, ~2–3 R_E [*Sergeev et al*., 1990; *Angelopoulos et al*., 1996, 1997; *Kauristie et al*., 2000; *Sergeev et al*., 2000; *Nakamura et al*., 2001, 2004]; however, these narrow plasma streams are capable of carrying magnetic flux at a rate comparable to that of large-scale magnetic flux circulation in the magnetosphere [*Angelopoulos et al*., 1994]. Using three-dimensional MHD simulations, *Birn et al*. [2004] investigated the dynamics of the magnetotail flux tubes with reduced entropy to address properties of the earthward motion of BBFs. They showed that earthward transport of depleted flux tubes leads to a BBF channel surrounded by region 1 sense field-aligned currents (FACs), downward field-aligned current on the

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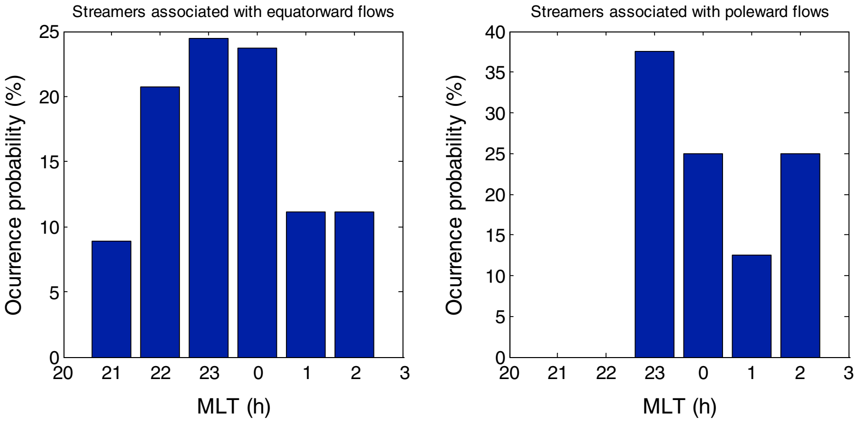

Figure 1. MLT distribution of the selected streamer events.

dawn side, and upward FAC on the dusk side. Similar relations between BBFs and field-aligned currents have been obtained by the Rice Convection Model as well [*Yang et al.*, 2011, 2012].

[3] It is known that the poleward boundary intensifications and their equatorward extension, auroral streamers, are the ionospheric signature of longitudinally localized earthward flow bursts in the plasma sheet [*Henderson et al.*, 1998; *Sergeev et al.*, 1999, 2000; *Lyons et al.*, 1999, 2002; *Kauristie et al.*, 2000; *Zesta et al.*, 2000; *Zou et al.*, 2010, 2013]. Those studies also found that the flows related to the streamers mapped to the east of the streamers, consistent with the relationship between the aurora and upward FACs on the duskside of the flow [*Amm et al.*, 1999; *Nakamura et al.*, 2001; *Birn et al.*, 2004].

[4] In contrast to the large number of studies on plasma sheet fast flows and conjugate auroral intensifications, localized, transient ionospheric flows in the auroral zone have not received much attention. The DMSP satellites have been used to identify the spatial relationship between equatorward flow channels and auroral streamers [*Sergeev et al.*, 2004]. Recently, *Shi et al.* [2012] investigated the 2-D pattern of ionospheric flows and auroral streamers using SuperDARN and the wideband imaging camera onboard the Imager for Magnetopause-to-Aurora Global Exploration satellite to measure flows and streamers, respectively. They showed that equatorward flow enhancements formed within and to the east of streamers. Their methodology provided an excellent view of the relationship between ionospheric flows and auroral streamers on large scales, but the low-spatial resolution of space-based imaging was a limiting factor. For a full understanding of the link between auroral streamers and flow structures in the ionosphere, higher resolution measurements are required. *Pitkänen et al.* [2011] used the KEVO all-sky imager and the European Incoherent Scatter VHF radar to identify auroral streamers and flow patterns in the ionosphere, respectively. The authors also reported a good correlation between auroral streamers and flow enhancements in the ionosphere and suggested that the equatorward flow enhancements are located to the east of the streamer. However, their radar observations were limited to a single line of sight, and the ionospheric backscatters were obtained outside the imager field of view, requiring spatial extrapolation of both radar and auroral observations.

[5] Here we present a detailed study of the association between auroral streamers and flow enhancements in the ionosphere using the Time History of Events and Macroscale Interactions during Substorms (THEMIS) all-sky imagers (ASIs) and Super Dual Auroral Radar Network (SuperDARN) radars that measure flows within the THEMIS ASI field of view. Radar echoes captured close to the radars (~500 km) were mainly used to detect small-scale flow structures that could be missed or would be poorly resolved in long-range radar echoes. We examined 135 isolated auroral streamers from December 2007 to December 2010 and identified flow patterns and their association with auroral streamers. We show that the equatorward and westward motion of the auroral streamers is well correlated with the flow enhancements. Finally, we provide evidence supporting the results obtained in the MHD simulations of *Birn et al.* [2004] relative to the flow vortex associated with field-aligned current formation.

2. Data Set and Methodology

[6] We use the THEMIS ASIs [*Mende et al.*, 2008] to identify auroral streamers. The ASIs are white light charge-coupled device imagers, where each imager has a latitudinal coverage of ~9° and a longitudinal coverage of slightly more than 1 h in magnetic local time (MLT) with time resolution of 3 s The SuperDARN radars were used to measure ionospheric flows. SuperDARN is a chain of high-frequency coherent scatter radars that measure the ionospheric *E* and *F* region flow velocity in the line-of-sight (l-o-s) direction with temporal resolution of 1 or 2 min [*Greenwald et al.*, 1995]. The SuperDARN radars scan through 16 beams (from east to west) of azimuthal separation of ~3°, where each beam is divided into ~100 (variable between radars) range gates. The radars used here are in Rankin Inlet (rkn), Inuvik (inv), Saskatoon (sas), Prince George (pgr), and Kapuskasing (kap), where their field of views (FOVs) are directed roughly poleward in the auroral zone and overlap with the FOVs of the Rankin Inlet, Gillam, Fort Smith, Forth Simpson, and Athabasca THEMIS ASIs. Since short-range radar echoes are generally *E* region echoes, where, because of collisions, the Doppler speed magnitude is not the full electric field drift, we do not compare the flow speed and auroral propagation speed but focus on flow structure, although we calculate average flow speeds. Even though

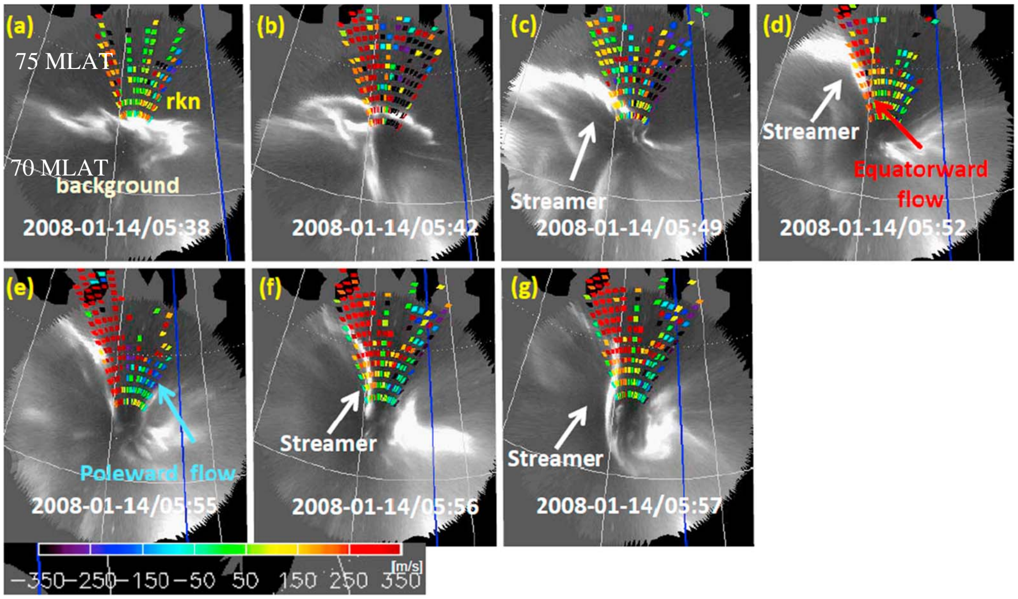

Figure 2. Equatorward motion of the auroral streamer and the ionospheric flow channel obtained using the THEMIS ASI and Rankin Inlet SuperDARN radar on 14 January 2008. (a) The background flows before the auroral streamer propagated into the radar FOV. (b–g) The sequence of flow and auroral streamers. The solid blue line indicates magnetic midnight. The white lines correspond to 75 and 70 MLAT contours, respectively.

the echoes are mainly due to *E* region backscatters, and thus, the magnitude of their Doppler speeds may be underestimated and limited below the ion acoustic speed (~400 m/s) [*Haldoupis*, 1989; *Koustov et al.*, 2005], this does not influence our results because we do not discuss the exact flow magnitude, but rather focus on relative flow changes.

[7] We examined THEMIS ASI data during fall and winter months (October to April) from mid-2007 to 2010. Auroral streamers are defined as roughly north-south-aligned arcs that originate from or near the poleward boundary of the auroral oval and propagate equatorward [*Zesta et al.*, 2002]. While some streamers are highly tilted to the east or west depending of the convection pattern [*Zesta et al.*, 2006; *Zou et al.*, 2009, 2010], we only selected streamers oriented roughly parallel to the radar l-o-s directions so that flows tangential to streamers can be measured by the radars. Tangential flows are generally stronger than normal flows for stable arcs [*Aikio et al.*, 2002], and such a pattern is also expected for auroral streamers since converging Pederson currents are believed to drive both stable arcs and streamers. In order to obtain flows associated with streamers, streamers should be measured within or adjacent to available radar echoes. We require that streamers are roughly parallel to the radar l-o-s direction and this frequently occurs within ±3 h of MLT around magnetic midnight, with maximum intensities higher than 3000 count/s. The longitudinal extension of the streamers should be fully covered within the available ASI FOVs. We further required that streamers are isolated, i.e., that there be no other streamer within the FOV of the observing radar at the same time. Fast flows should be more than 200 m/s to be easily identifiable.

[8] We found 135 isolated streamers that satisfied the criteria above. Most of these, 90% (121 events) showed equatorward flow enhancements associated with the streamers, 10% (11 events) showed poleward flows, and 3% (4 events) showed both equatorward and poleward flows. Figure 1 shows the MLT distribution of these equatorward (Figure 1a) and poleward (Figure 1b) flow events. On average, streamers with equatorward flows were more frequently identified before magnetic midnight, and streamers with poleward flows appeared to be more frequently observed around magnetic midnight. It is interesting to notice that there are no streamer events after 2 MLT in this study, and also, there are no streamers associated with poleward flows before 23 MLT. The number of poleward flow events at each MLT is less than one third of that of equatorward flows, and we do not reach a conclusion about the relatively higher occurrence of poleward flows at postmidnight. The lack of streamers before 21 MLT and after 2 MLT is probably because we focus on streamers nearly parallel to the radar l-o-s direction, which is roughly in the north-south direction. When considering the large-scale two-cell-flow pattern, equatorward flows near midnight turn azimuthally and propagate sunward as they propagate away from midnight. Such azimuthally oriented flows and streamers are not included in our study.

3. Results

3.1. Representative Cases

[9] In this section, we analyze in detail four events that illustrate the relationship between streamers and flow channels.

[10] Figure 2 shows a streamer moving equatorward within the Rankin Inlet radar FOV on 14 January 2008. The black-white images were obtained using the THEMIS ASI and the colored rectangles correspond to the l-o-s velocity measured by the SuperDARN radar, which is located near the center of the imager FOV. Warmer colors correspond to l-o-s flows toward the radar (roughly equatorward) and

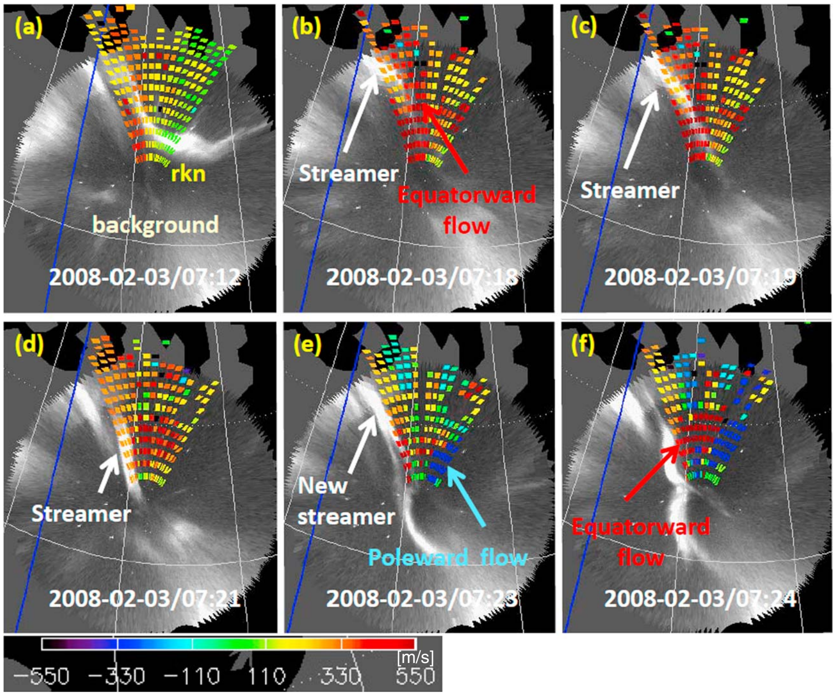

Figure 3. Panels represent the equatorward motion of the streamer and the related flow channel on 3 February 2008. The format is the same as in Figure 2.

colder colors are flows away from the radar (poleward). Figure 2a shows a snapshot before the poleward motion of an arc along the auroral poleward boundary. The l-o-s velocities were small except for a moderate flow near the western edge of the radar FOV. The western portion of the poleward boundary arc moved poleward in Figures 2b–2d. Figure 2b shows that enhanced equatorward and poleward flow developed poleward of the arc, which could be related to the channels of enhanced polar cap flows recently reported by *Zou et al*. [2013]. Then, a streamer (>5000 c/s in intensity) originated from the eastern side of the poleward moving arc and propagated into the radar FOV (Figures 2c and 2d). Associated with this auroral streamer, an equatorward flow enhancement of ~300 m/s was observed just to the east of the auroral streamer. The streamer propagated further equatorward roughly aligned with the radar l-o-s direction, and the enhanced equatorward flow also extended equatorward (Figures 2e–2g). Also, a poleward flow enhancement was detected to the east of the equatorward flow (Figure 2e) and further enhanced in Figures 2f and 2g.

[11] In Figure 3, we present another event showing the association between flow pattern and auroral streamer. Figure 3a shows flow and auroral structure that lasted for 4 min before the streamer of interest. Preceding this, slowly drifting streamers were detected, and flows were weak except for a moderate flow near the western edge of the radar FOV. Figure 3b at 0718 UT marks the initiation of the streamer in the northwestern portion of the radar FOV and of an equatorward flow enhancement. While the enhanced flow appears to extend deeper equatorward than the streamer, this is likely due to the limited time resolution of the radar (2 min), and the streamer did extend down to ~73° MLAT in the next minute (Figure 3c). The streamer propagated further equatorward almost parallel to the radar l-o-s direction in Figures 3d–3f and the equatorward flow remained enhanced. Another streamer formed in the northwestern portion of the radar FOV at 0723 UT (Figure 3e) and propagated equatorward along the same path. During the propagation of this second streamer, the enhanced equatorward flows extended significantly (~0.2–0.5 h in MLT) to the east of the streamer and were aligned with the streamer. In addition, at 0723–0724 UT, the radar measured a poleward flow enhancement further to the east of the radar FOV. In both examples shown above, the existence of an equatorward flow just to the east of a streamer is consistent with an upward FAC on the western edge of a plasma sheet BBF [e.g., *Birn et al*., 2004]. The poleward ionospheric flows on the eastern side of the equatorward ionospheric flows would correspond to tailward plasma sheet flows as part of flow vortices. The resultant counterclockwise ionospheric flow vortex is an indication of a downward FAC sheet, the counterpart of the upward FAC flowing on the streamer field lines. Thus, the combination of auroral imaging and ionospheric flow observations allows us to infer the 2-D structure of the FAC pair and related flows.

[12] The streamer in Figure 4 shows a westward drift in addition to its equatorward propagation. As tracked by the white arrows, the streamer was initially located to the east of the radar FOV and then reached near the center of the radar FOV. The azimuthal motion of this long-lasting streamer allows us to scan the 2-D distribution of the l-o-s flow as it drifted across the radar FOV. In Figure 4a, a very strong poleward flow was measured in the middle of the radar FOV to the west of the streamer. As the streamer moved westward in Figures 4b–4f, the poleward flow region also moved in the same way and an equatorward flow appeared near the eastern edge of the radar FOV. The streamer marks

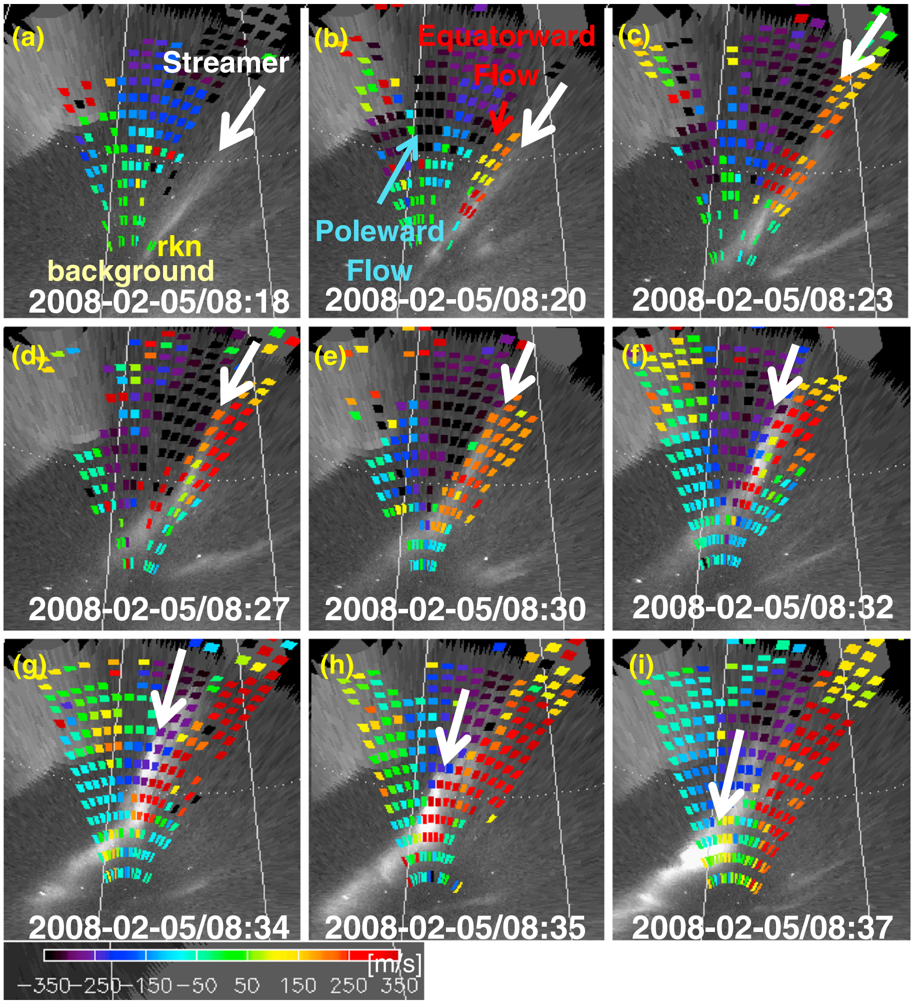

Figure 4. 5 February 2008 event illustrating the azimuthal and equatorward motion of the streamer and the correlation with the flow channel.

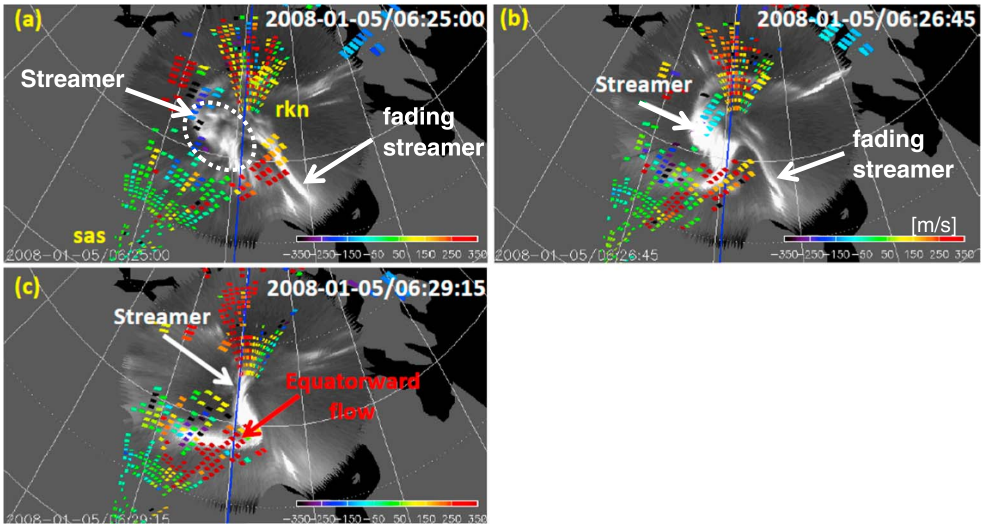

Figure 5. Flow channel associated to the auroral streamer detected in two radars.

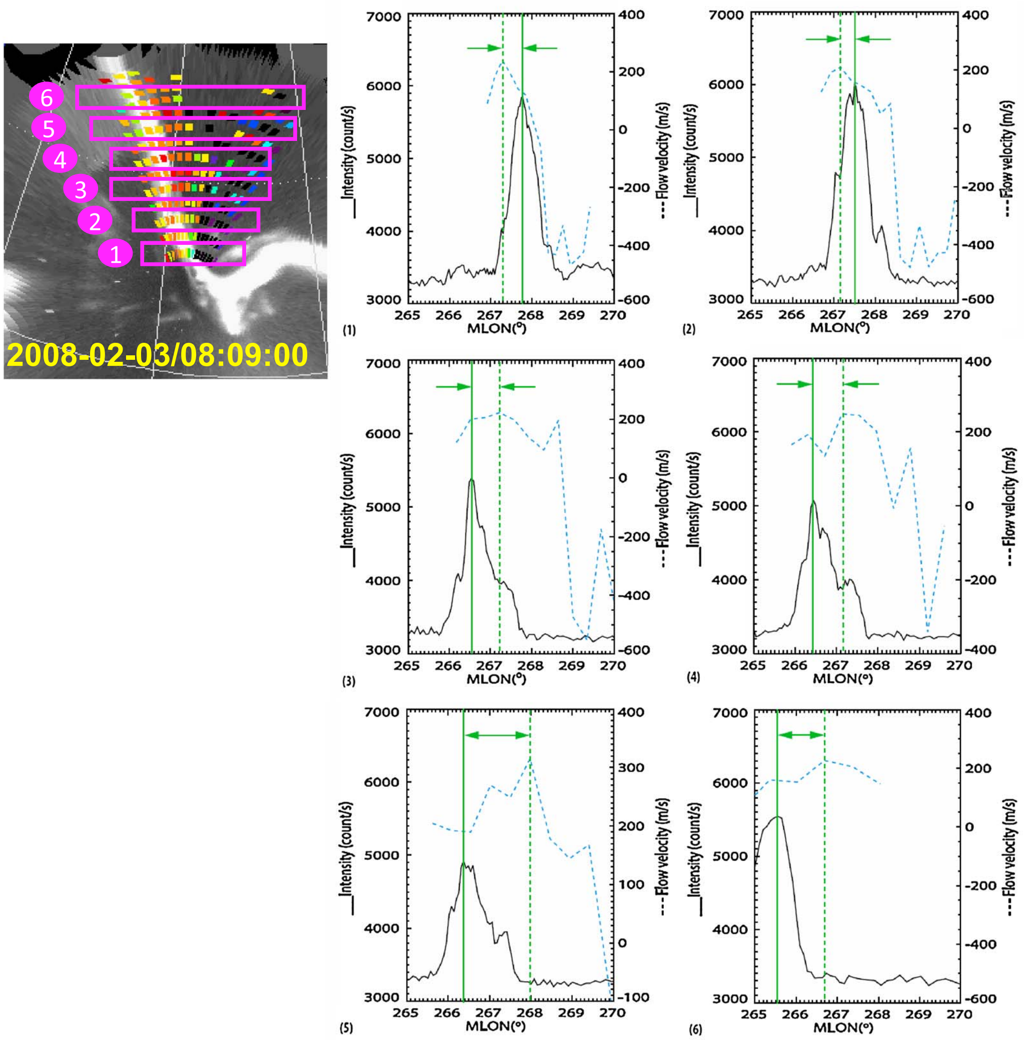

Figure 6. Latitudinal cuts along the radar FOV to determine the azimuthal width and shift of each auroral streamer. The left figure shows an example of six latitudinal cuts made for the 3 February 2008 event. The right panels represent auroral intensity (solid back line) and flow speed (blue dashed line), both as a function of magnetic longitude for each of the cuts shown in the figure on the left. The vertical solid (dashed) green lines correspond to the streamer's maximum intensity (maximum flow velocity). The green arrows indicate the azimuthal shift for each cut.

the boundary between the poleward and equatorward flows, consistent with an upward FAC sheet at the clockwise flow shear. The streamer intensified, and the intensification rapidly propagated equatorward from Figure 4e to Figure 4i, and the equatorward flow intensified and also moved equatorward with the streamer.

[13] In limited occasions, when the streamers extend through the FOVs of the two consecutive radars with sufficient echoes, it is possible to observe the flow enhancements associated with streamers in both radars at the same time. Figure 5 shows one example of a latitudinally long streamer starting in the Rankin Inlet FOV and reaching the poleward region of the Saskatoon radar FOV. In Figure 5a, a streamer started to intensify near the center of the ASI image and fast flows toward the radar were observed by the Saskatoon (sas) radar. Another streamer was present to the east of it and was gradually fading. This streamer was oriented perpendicular to the radar l-o-s direction and thus would not affect the measured flows. The streamer near the center of the imager FOV further intensified and extended equatorward and westward (Figures 5b and 5c), and a fast equatorward flow channel was then observed in both the Rankin Inlet and the Saskatoon radar FOVs just to the east of the streamer. This event demonstrates that enhanced flow channels are not limited to the latitudinal extent of the radar FOV but can extend over wide latitude ranges (~10° in this case) adjacent to the streamers.

3.2. Statistical Study

[14] Using all 135 streamer-flow conjunction events, we examine if the flow structure obtained in the above cases is common. To accomplish this, we calculate the azimuthal width and offset of the equatorward and poleward flow enhancements relative to that of the auroral streamers and

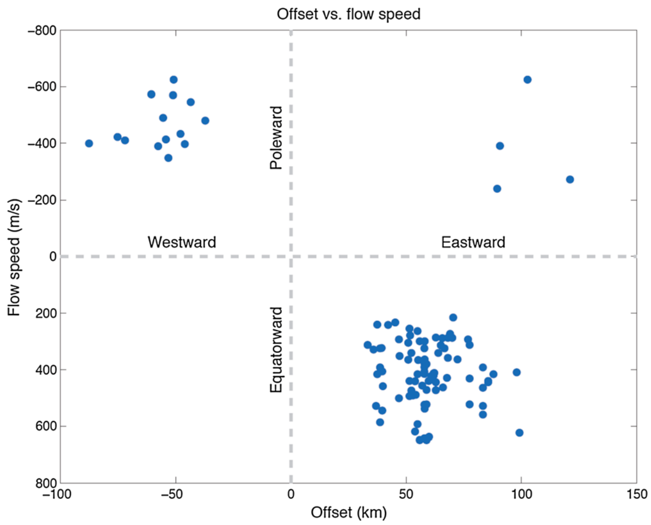

Figure 7. Azimuthal offset of ionospheric flow channels as a function of flow speed. Positive values of flow speed indicate equatorward flow enhancement and negative values represent poleward flow enhancement.

the average values of the maximum intensity of the auroral streamer and the average flow speed.

[15] Six longitudinal cuts along the radar FOV were made every two or three range gates (depending on the echo availability) to determine the azimuthal width and location of enhanced flows. An example for one of the events is shown in Figure 6 (left). The auroral intensity and flow velocity along each slice are shown on the first and second columns. At the time of the flow channel width measurements, echoes were available at ≥70% of the radar measurement locations within the overlapping portion of the radar and ASI FOVs. In addition, the flow channel width was calculated when the edges of the channel were more than one beam width away from the eastern and western edges of the radar FOV. For this time, we fit a Gaussian curve around the maximum flow velocity to calculate the full width at half of the maximum (FWHM) for each cut and then we calculate the width as the average FWHM over the cuts. We also calculate the azimuthal shift of the location of the maximum flow speed with respect to the location of the maximum intensity of the auroral streamer. In this example, the peak flow velocity is shifted to the east of the streamer by ~1° on average and the azimuthal width of the flow enhancement is ~100 km (2.3°).

[16] Figure 7 shows the azimuthal offset of the flow channels relative to the associated streamer. The x axis gives the flow speed. Negative (positive) flow speeds represent poleward (equatorward) motion. The y axis is the azimuthal offset of the maximum flow speed relative to the position of the associated auroral streamer's maximum intensity. Positive offsets correspond to flow channels to the east of their respective streamers. We see that all equatorward flow enhancements (positive flow speeds) are located to the east of their respective auroral streamer. In contrast, poleward flow enhancements are mostly to the west of the auroral streamers, although a few do not follow this trend. For a few events (e.g., Figure 6), it was possible to observe an equatorward flow enhancement to the east of the streamer and a poleward flow to the west of the streamer within the same radar FOV, and both are included in Figure 7. This three-direction structure of flows (poleward-equatorward-poleward) is consistent with the plasma flow shears around a BBF channel [*Birn et al.*, 2004]: The streamers coincide with the upward FAC sheet at the western edge of the equatorward flow channel, that is associated with a flow shear exhibiting clockwise ionospheric flow vorticity (viewed from space). A downward FAC sheet is expected at the eastern edge of the equatorward flow channel, within a flow shear that exhibits a counterclockwise flow vorticity. Note in Figure 7 that there are fewer points with poleward flows than with equatorward flows. While flows will be sometimes missed due to the limited size of the radar FOV, our criteria for event selection should not favor equatorward flows over poleward flows, or poleward flows to the west of streamers than those to the east. Based on the *Birn et al.* [2004] simulations, a reasonable explanation of the lower number of observations of poleward flow enhancement is that the poleward flows (tailward in the plasma sheet) do not extend as far in latitude as do the equatorward (earthward) flows (see Figure 18 in the work of *Birn et al.* [2004]). Such poleward flows are expected to be located at the equatorward portion of the auroral oval, which map to the near-Earth plasma sheet, where earthward flows deflect and form flow vortices. Since the Rankin Inlet radar is typically located at the high latitude portion of the auroral oval, many of the poleward flows would be located equatorward of the radar FOV. Also, it is particularly difficult to detect the poleward flows to the east of the equatorward flows, since those are quite far away from the streamers, and we require the streamers to be located within or adjacent to the radar FOV. However, based on a frequent occurrence of poleward flows to the west of the streamer, we consider that the poleward flows are commonly associated with the streamers and are a useful indicator of the FAC pair locations.

Table 1. First and Second Column Represent Average Width and Flow Speed Relative to the Flow Enhancement, and Third Column Shows the Auroral Streamer Maximum Intensity for Events Shown Equatorward and Poleward Flow Enhancements, Respectively

	Average Width (km)	Flow Speed (m/s)	Intensity (c/s)
Equatorward flow	73 ± 24	427 ± 171	5375 ± 1991
Poleward flow	76 ± 29	−453 ± 70	4075 ± 807

[17] The first and second columns in Table 1 show the width and average flow speed for equatorward and poleward flow enhancements, and the third column shows the maximum intensity of the auroral streamer. We see that the azimuthal widths of the flow enhancements are essentially the same, 73 ± 24 km and 76 ± 29 km for the equatorward and poleward flow enhancements, respectively. The average flow speeds of poleward and equatorward flows are also about the

Table 2. Average Azimuthal Shift[a]

	Azimuthal Shift (km)	% Total Events
Eastward shift	58 ± 13	90
Westward shift	56 ± 13	10

[a] Eastward (westward) shift correspond to maximum flows speed located to the east (west) of the streamer maximum intensity.

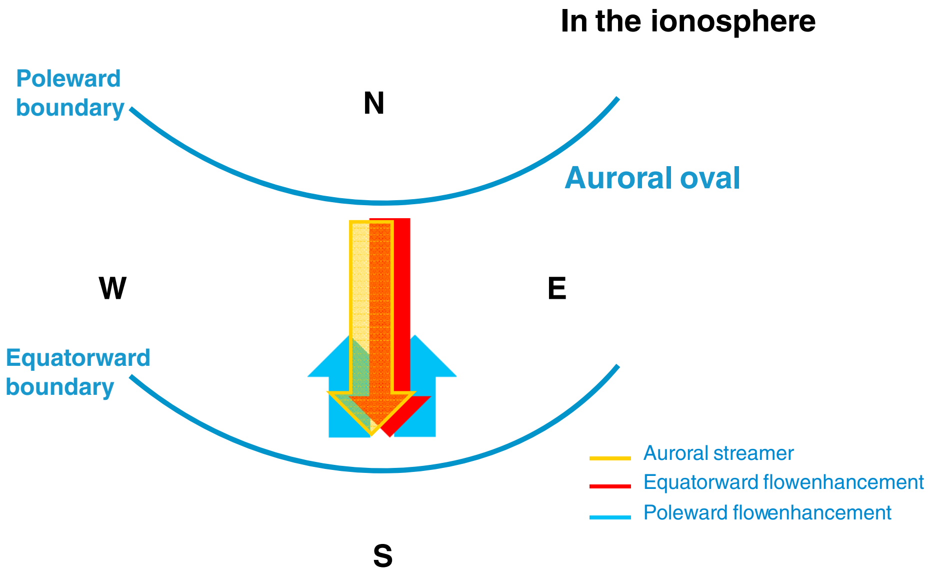

Figure 8. Schematic illustration of the association between auroral streamers and flow enhancements in the ionosphere.

same, as we can also see in Figure 7. We note that, while these flow channel widths are much narrower than the radar FOV width (207 km at 75° MLAT), our short-range echoes are not able to capture wide flow channels as were analyzed by *Shi et al*. [2012]. Our data set focuses on mesoscale flow channels and streamers that are more frequently seen.

[18] We also calculated the azimuthal shift as the difference between the positions of the maximum flow velocity with respect to the maximum intensity of the auroral streamer. The average azimuthal shift for both equatorward and poleward flow enhancements is about 58 km (Table 2). The four events for which it was possible to observe both equatorward and poleward flows within the radar FOV on either side of the streamer were also considered in this part of the analysis.

[19] Based on the *AL* index during these streamer events, 53% of events occurred during the recovery phase of substorms (slow recovery of *AL* after a sharp intensification), while the rest 47% are observed during quiet times ($AL > -100$ nT). We do not have expansion phase events, although intense streamers are often seen during the expansion phase. This is because expansion phase streamers are so dynamic and frequent that it is difficult to find isolated streamers.

4. Conclusions

[20] Taking advantage of the high-spatial and temporal resolution of the THEMIS ASIs and the high-spatial resolution of the short-range SuperDARN radar that overlap spatially with the ASI imagers, we investigated statistically the properties of ionospheric flows related to auroral streamers.

[21] By selecting 135 isolated streamers roughly aligned with the radar l-o-s directions, we found that all streamers are correlated with fast flows around the streamers, and most of them were directed equatorward. The equatorward flows invariably lie just to the east of their respective streamer. While observed less frequently, we found evidence for two poleward flows to the east and west of the equatorward flow, giving a three-flow structure as illustrated in Figure 8. The western edge of the equatorward flow is collocated with the streamer, which highlights an upward FAC sheet. While the eastern edge of the equatorward flow does not have any auroral emission, it is likely the location of a downward FAC sheet that is a counterpart of the upward FAC. We calculated the azimuthal width of the equatorward and poleward flow enhancements obtaining an average of about 74 km for both cases. We also calculated the azimuthal shift of the maximum flow speed relative to the maximum intensity of the streamer obtaining an average of 58 km for both equatorward and poleward flow enhancements.

[22] The flow structure we found is consistent with MHD simulations [*Birn et al*., 2004] and multisatellite observations [*Keiling et al*., 2009] during BBFs in the plasma sheet. Our results suggest that ground-based observations are quite useful for identifying the 2-D structure of localized flows and FACs that cannot be easily obtained by in situ observations in the plasma sheet.

[23] We have mapped the flow channel widths for the case studies from the ionosphere to the magnetosphere using Tsyganenko 2001 as an external model and the International Geomagnetic Reference Field (IGRF) model for the Earth's magnetic field, and we obtained an average flow channel width of 1.5 R_E. Here the flow channel width is defined as the FWHM of the radar observations. However, there is a considerable amount of flow enhancement outside this range, and if we lower the flow magnitude threshold to 100 m/s, the corresponding magnetospheric width increases to 2.6 R_E. Both numbers are roughly consistent with the result obtained by *Nakamura et al.* [2004] within the plasma sheet.

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