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Key Points:

- Substorm onsets with appropriate auroral and radar viewing provide further evidence that intruding flow channels lead to substorm onsets
- The reduced entropy of intruding plasma indicates change in plasma sheet entropy distribution gives rises to the substorm onset instability
- Further evidence that flow channels leading to onset move into the plasma sheet/auroral oval from the polar cap, open-field-line region

Supporting Information:

- Supporting Information S1
- Figure S1
- Movie S1
- Movie S2
- Movie S3
- Movie S4
- Movie S5
- Movie S6
- Movie S7

Correspondence to:

L. R. Lyons,
larry@atmos.ucla.edu

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Radar Observations of Flows Leading to Substorm Onset Over Alaska

Larry R. Lyons[1], Jiang Liu[2], Yukitoshi Nishimura[3], Ashton S. Reimer[4], William A. Bristow[5], Don L. Hampton[5], Xueling Shi[6], Roger H. Varney[4], and Eric F. Donovan[7]

[1]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, CA, USA, [2]Department of Atmospheric and Oceanic Sciences and Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, Los Angeles, CA, USA, [3]Center for Space Physics and Department of Electrical and Computer Engineering, Boston University, Boston, MA, USA, [4]Center for Geospace Studies, SRI International, Menlo Park, CA, USA, [5]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA, [6]Department of Electrical and Computer Engineering, Center for Space Science and Engineering Research, Blacksburg, VA, USA, [7]Department of Physics and Astronomy, University of Calgary, Calgary, AL, Canada

Abstract About 40 years after the discovery of the substorm, auroral observations were used to propose that substorm onset was triggered in the inner plasmas sheet (equatorward portion of the auroral oval) by an intrusion of the low entropy plasma by plasma sheet flow channels. Longitudinal localization makes such flow channels difficult to observe with sparse spacecraft, but they can be seen in the ionosphere via the broader, two-dimensional coverage by ground-based radars. We have analyzed all eight substorm auroral onset events with appropriate auroral and Poker Flat radar viewing during a radar campaign. These, together with five previously analyzed events provide evidence that intruding flow channels play an important role in substorm onsets. That the flux tube integrated entropy of this new plasma must be lower than that of the surrounding plasma implies that the change in the entropy distribution within the plasma sheet gives rises to the substorm onset instability that is seen via the growing auroral and electromagnetic waves seen with substorm auroral onset. Our analysis also adds to previous evidence that the flow channels leading to onset move into the plasma sheet/auroral oval from the open polar cap region of the magnetotail lobes/polar caps, that these flow channels move across the polar cap following their origin near the dayside boundary of the polar cap, and that substantial ground magnetic depressions associated with substorm do not occur with substorm onset but instead occur a few to several minutes later in association with expansion phase streamers.

1. Introduction

The arc near the equatorward boundary of the auroral oval that brightens and expands poleward identifies the onset of the substorm expansion phase (Akasofu, 1964). Its mapping along magnetic field lines is likely to the near-Earth portion of the electron plasma sheet (Samson et al., 1992), near the region where the magnetic field transitions from being highly stretched to more dipolar (e.g., E. Donovan et al., 2008; Sergeev et al., 2012, and references therein). Initial brightening involves wave-like modulation of auroral intensity and latitudinal position along the arc, giving the visual appearance of auroral beads (E. F. Donovan et al., 2006; Kalmoni et al., 2017; Motoba et al., 2012; Y. Nishimura et al., 2016; Sakaguchi et al., 2009). Each wave is associated with intense electric fields (Gallardo-Lacourt, Nishimura, Lyons, Ruohoniemi, et al., 2014; ;Gallardo-Lacourt, Nishimura, Lyons, Zou et al., 2014; Hosokawa et al., 2013), and the auroral waves grow in amplitude following their initiation and then evolve into nonlinear structures (Lyons, Nishimura, Donovan et al. 2013; Lyons, Nishimura, Gallardo-Lacourt et al., 2013, and references therein).

These observations imply that substorms are initiated by an instability within the near-Earth plasma sheet. This introduces the fundamental questions of what are conditions that lead to this instability and what is the physics of the instability. In this study, we provide direct observations of ionospheric flow that supports the flow channel triggering of the onset instability that has previously received strong support from auroral imaging but has only been investigated with flow observations in a very few cases (L. R. Lyons et al., 2010; Nishimura, Lyons, Nicolls, et al., 2014). We also show observations indicating that triggering flow channels are connected to dayside processes. In the companion paper (L. R. Lyons et al. 2020), we extend this observational analysis to show how the same flow channels may exert control on the azimuthal expansion of substorm expansion phase activity after onset.

Auroral streamers correspond to fast channels, which extend along field lines from the plasma sheet to the ionosphere. It is important to note the growth of auroral beading structures can lead to strong auroral streamers and associated flow channels during the ensuing substorm expansion phase (Keiling et al., 2009; Lyons, Nishimura, Donovan et al., 2013; Lyons, Nishimura, Gallardo-Lacourt et al., 2013; Rae et al., 2009). These expansion phase flow channels typically have stronger signatures than do the flow channels believed to be associated with the substorm onset instability. They initiate the traditional substorm ground magnetic signatures and magnetic dipolarization within the near-Earth plasma sheet, are likely associated with reconnection signatures seen within the plasma at X_{gsm} distances of ~−20 R_E soon after substorm onset (Machida et al., 2009; Nishimura, Lyons, Shiokawa, et al., 2013), and likely work together lead to form the substorm current wedge (Gabrielse et al., 2019; Liu et al., 2013; Lyons, Nishimura, Donovan, et al., 2013; Lyons, Nishimura, Gallardo-Lacourt et al., 2013; T. Nishimura et al., 2012; X. J. Zhang et al., 2011). Thus, the onset instability within the inner plasma sheet is followed by other well-known signatures of substorms, particularly current wedge formation, ground magnetic depressions, and near-tail reconnection.

Flow channel triggering of onset was proposed by Nishimura et al. (2010) using observations from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) all sky imager (ASI) array, which gives high temporal and spatial resolution auroral images with broad longitudinal and latitudinal coverage (Mende et al., 2008). They found evidence that auroral forms, now commonly referred to as auroral streamers, extend equatorward to the vicinity of the location of auroral onset and appear to trigger onset. The initiation of the streamer, appearing as a poleward boundary intensification, occurred on average ~5.5 min prior to onset. In about 50% of events, onset was observed where and when the streamer approached growth phase auroras within the equatorward portion of the auroral oval. For other events, the auroral streamer turned into enhanced auroral brightness that moved azimuthally along the growth phase aurora and onset occurred when the azimuthally moving enhanced auroral brightness reached the onset location. This azimuthal motion was typically westward, consistent with onset within the duskside convection cell, but was eastward in a few cases, consistent with some onsets occurring within the dawnside convection cell.

Streamers lie near the right edge (when looking along the flow direction in the northern hemisphere) of narrow flow channels in the ionosphere where ionospheric Pederson currents converge (Gallardo-Lacourt, Nishimura, Lyons, Zou et al., 2014), and these flows are the mapping of narrow, enhanced earthward flows within the plasma sheet (Angelopoulos et al., 1996; Haerendel, 2011; Henderson et al., 2002; Nakamura et al., 2004; Pitkänen et al., 2011; Rostoker et al., 1987; Sergeev et al, 1996, 1999, 2000; Zesta et al., 2000). It is now generally believed that these plasma sheet flow channels (often referred to as "flow bursts" or "bursty bulk flows") consist of depleted magnetic flux tubes (i.e., flux tubes with lower total entropy than the surroundings, sometimes referred to as "bubbles") (Dubyagin et al., 2010; Panov et al., 2010; Pontius & Wolf, 1990; Sergeev et al., 1996, 2012; Wolf et al., 2012; Xing et al., 2010; Yang et al., 2011). This implies that plasma sheet flow channels trigger onset instability by bringing reduced entropy plasma to the inner plasma sheet, the low-entropy plasma being brought earthward within a plasma sheet flow channel by interchange motion. However, the onset instability is very different from such earthward (equatorward as mapped to the ionosphere) interchange motion, since onset extends longitudinally along an east-west oriented auroral arc near the equatorward boundary of the auroral oval.

The observed relation between auroral streamers and substorm onset leads to the suggestion that onset is due to the intrusion of the new, reduced entropy plasma to near the inner edge of the electron plasma sheet. It seems plausible that an intrusion of low entropy plasma to the inner plasma would greatly reduce the outward radial gradient of entropy within the inner plasma sheet (which is critical for plasma sheet stability, e.g., Xing & Wolf, 2007), perhaps even locally reversing its sign, leading to a ballooning type of instability such as the kinetic ballooning/interchange instability found by Pritchett et al. (2014) using three-dimensional electromagnetic particle-in-cell simulations. Furthermore, such intruding plasma is expected to expand azimuthally within the plasma sheet via the combination of dawnward electric field drift just tailward (poleward in the ionosphere) of the Harang reversal and the duskward magnetic drift of the more energetic particles (Wang et al., 2018; J. Yang et al., 2014) (Magnetic drift not only expands a bubble in the duskward direction, but also gives a divergence of the heat flux vector [L. R. Lyons et al., 2009], which acts to reduce the entropy of the bubble plasma and thus could enhance the chances of instability). The longitudinal expansion of a bubble offers a plausible explanation for why the onset instability expands longitudinally within the equatorward portion of the auroral oval, and why the instability can occur at a longitude displaced from the location of an incoming flow channel.

However, direct observation of the flow to the onset location has been very limited, there being only five published events. For four events, flow vectors along the magnetic meridian from the Poker Flat Incoherent Scatter Radar (PFISR) were used to evaluate flows coming to an onset observed to be within, or near, the field-of-view (FOV) of the radar (L. R. Lyons et al., 2010) (The flow vectors are a routine PFISR data product calculated using a Bayesian inversion that provides a best-fit to F-region flow velocities as a function of latitude [Heinselman & Nicolls, 2008]. The inversion incorporates LOS velocities from all PFISR beams under the assumption of no longitudinal variations with the radar FOV.) For two of the events, enhanced flows entered the onset region from the poleward direction, consistent with the direct triggering of the onset instability by the incoming flow channel for the other two events, enhanced westward flows reached the onset location within the subauroral polarization streams (SAPS) region equatorward of the Harang reversal. As seen in the results of Wang et al. (2018) and discussed further in the companion paper, such enhancements of SAPS flow are expected to accompany an intruding bubble as it expands westward from magnetic drift with its equatorward boundary near the poleward boundary of the SAPS region.

For one event in a more recent study, Nishimura, Lyons, Nicolls et al. (2014) took advantage of the detailed radar line of sight flow observations for an onset initiating within the PFISR FOV during a period of dense spatial coverage by 41 radar beams. They also used the high-quality color auroral imager at Poker Flat that began operation in late 2011. The Y. Nishimura, Lyons, Nicolls et al. (2014) event was during a PFISR radar campaign, called PFISR Ion Neutral Observations in the Thermosphere (PINOT) (Makarevich & Bristow, 2014), where PFISR was operated for much longer time intervals than usual (12 and 16 continuous nights) in special operation modes together with supporting instruments including high-resolution colored ASIs. Furthermore, there have not been any published concurrent observations of 630 nm optical emissions associated with observed flow channels leading to substorm onset. Such emissions, if they show polar cap patches moving toward the onset region, would support the existence of the observed flow channels leading to onset and imply they had their origin from processes near the dayside polar cap boundary.

Here, we add to the events in the above limited studies by examining the 15 PINOT nights (November 9, 2012 and March 3, 2013) with good auroral viewing conditions at Poker Flat. From the auroral observations during these nights, we identified 8 events in addition to the November 7, 2012 event in Nishimura, Lyons, Nicolls et al. (2014) for which a substorm auroral onset was identified within the FOV of the Poker ASI 557.7 nm observations and within or just equatorward of the latitudinal coverage of the PFISR beams. We analyze all the detected onsets, including the onsets that expanded poleward to a full substorm and those with limited poleward expansion (i.e., pseudo-substorms). Both have the same auroral onset features and our emphasis in this study is on what triggers onset, and not on what controls the ensuing expansion phase development. While they are not all isolated substorms, they are not a rebrightening of preceding activity but a clean onset that is separate from preceding activity.

We also consider observations of 630 nm optical emissions by the Poker Flat color imager to determine if we see evidence of polar cap patches or polar cap arcs moving toward the onset region. Such evidence would support the existence of the observed flow channels leading to onset. It is also important that the auroral streamers, and thus plasma sheet flow channels, originate from auroral poleward boundary intensifications (PBIs) along the auroral poleward boundary, and that PBIs are often driven by mesoscale flow enhancements that approach the nightside auroral oval from the polar cap. Such flow channels can be identified by ionospheric flow observations (e.g., de la Beaujardière et al., 1994). They can bring enhanced F-region ionization from the dayside that is detectable in 630 nm optical emissions as polar cap patches (Lorentzen et al., 2004; Moen et al., 2007; Zou, Nishimura, Lyons, Donovan, et al., 2015) or be detected by a polar cap auroral arc (Zou, Nishimura, Lyons, Donovan, et al., 2015; Zou, Nishimura, Lyons, Shiokawa et al., 2015). The existence of a polar cap patch or arc indicates that a flow channel had its origin from processes near the dayside polar cap boundary.

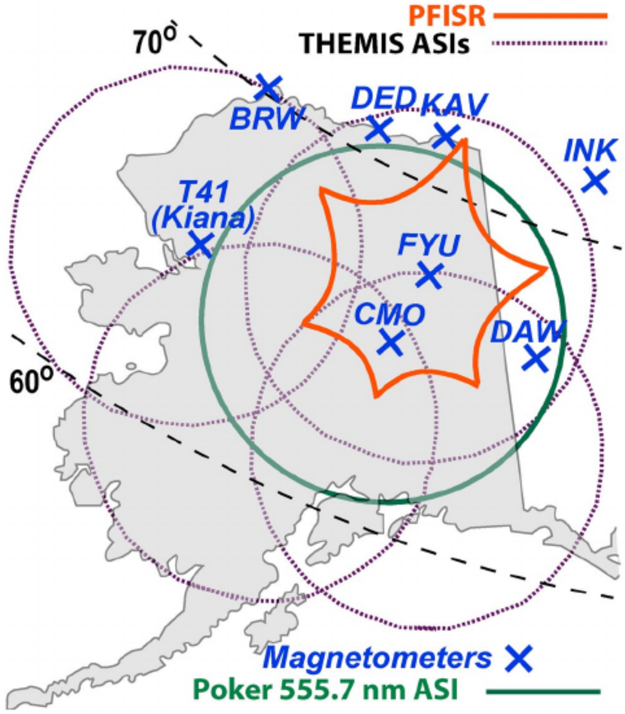

Figure 1. FOVs of the Poker Flat 557.7 nm images, the THEMIS ASIs in the Alaskan sector, and the PFISR radar. Also shown are ground magnetometer locations. ASI, all sky imager; FOV, field-of-view; PFISR, Poker flat incoherent scatter radar; THEMIS, time history of events and macroscale interactions during substorms.

2. Data Description

We examine the radar flows associated with the onsets in two ways, with the line-of-sight (LOS) flows measured along the radar beams and with flow vectors along the PFISR magnetic meridian from the standard Bayesian inversion mentioned in the Introduction. We use both, since there are ambiguities in the interpretation of the LOS flows in terms of two-dimenisonal flows, whereas the Bayesian inversion provides objective flow vectors but ignores longitudinal variations. Consistency between the two improves confidence in the interpretation of the observed flow variations with latitude and time. Furthermore, the PFISR flow vector product includes estimated errors, and we only show flow vectors having estimated magnitude error less than both the flow magnitude and 1 km/s. LOS velocities along Super Dual Auroral Radar Network (SuperDARN) radar beams (http://vt.superdarn.org/tiki-index.php) are also included where echoes are available. PFISR data can be integrated at any chosen time resolution, and we have chosen 1 min for all data used here (We also tried 15 s integration time, but the results were too noisy to be useful). In addition to the 557.7 nm images, we examined Poker ASI 630 nm images for signatures of polar cap patches moving toward the onset location, images from the THEMIS white light ASIs that cover regions surrounding that covered by the Poker ASI, and ground magnetometer observations from available station in the vicinity of the Poker Flat observations. The magnetometer observations show, consistent with our prior analysis (Lyons, Nishimura, Donovan et al., 2013; Lyons, Nishimura, Gallardo-Lacourt et al., 2013), that strongest ground magnetic responses, traditionally viewed as signatures of substorm onset, are related to postonset auroral streamers and not to the substorm onset seen in aurora. Figure 1 shows a map of Alaska that illustrates the coverages of the Poker 557.7 nm ASI, of the THEMIS white light ASIs, of PFISR, and the locations of the ground magnetometers used in this study.

3. Observations

3.1. Event 1: November 21, 2012, 0803:20 UT Onset

We first consider a substorm with onset seen in the aurora at 0803:20 UT on November 21, 2012. Images and radar LOS flows of this event are shown in Figure 2 (see caption for description). Text S2 in supporting information shows a three-panel movie with full time resolution images (every ~12 s). The left and center panels, respectively, show 557.7 nm images overlaid with the PFISR LOS velocities along radar beams and the PFISR flow vectors and SuperDARN LOS velocities. The right panels show 630 nm images overlaid with PFISR plasma densities along the radar beams. Radar observations in S2 are stepped in time with the appropriated radar time resolution. The substorm onset times for this and subsequent events were identified from such movies, which allowed the initial brightening to be identified within ~12 s accuracy. This was a full substorm onset, and the ground magnetometer data in supporting information Text S1 (which gives ground magnetometer data for all 8 events considered here) shows a significant ~350 nT ground magnetic north N component drop. However, this drop was not related to the substorm onset, but instead incurred at ~0815 UT in associated with intense expansion-phase auroral streamers that formed during the poleward expansion well after onset.

Initially (0800 UT), the flow vectors show westward flow as expected from dusk cell convection, and the LOS flows are consistent with this inference. The aurora shows a typical east-west oriented arc very near the equatorward limit of the PFISR beam measurements, this arc being typical of what is seen during a late substorm growth phase Then, the flow vectors turn toward the equatorward direction as seen at 0802:05 UT. Since the flow channel size is not known, it is unclear if the assumption of azimuthally uniform flow is

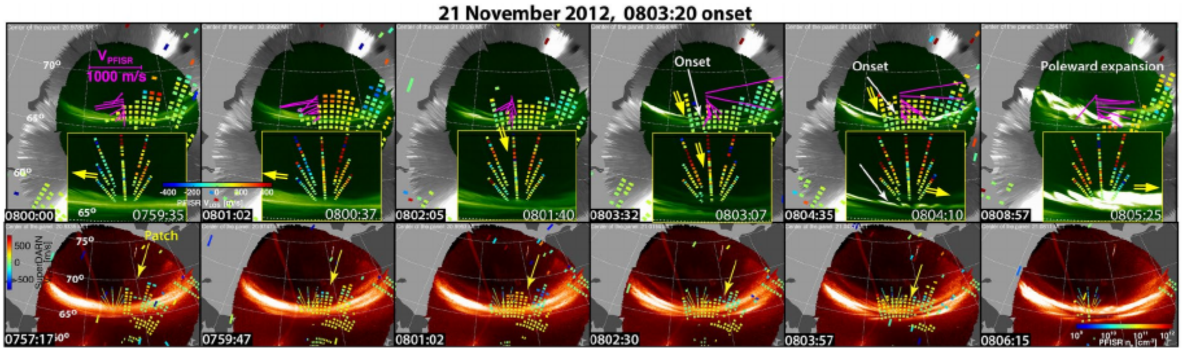

Figure 2. The upper panels show 557.7 nm images from Poker, with THEMIS ASI image mosaics for the region surrounding the Poker image FOV for event 1, the November 2012 21, 0803:20 onset. Images are shown every ~1 min, except for last image which was chosen to show the substorm poleward expansion ~4 min after the previous image. Objective flow vectors along the PFISR magnetic meridian are overlaid on the 557.7 images in each panel. LOS flows measured along the radar beams are shown overlaid on the lower image inserted into each of the 557.7 panels. These lower images are blowups of the 557.7 nm images over the region covered by the PFISR beams, and, to not repeat images, these images, which have 12 s time resolution, are for a slightly earlier time than the time of the full mosaics (except for the last panel), but during the same 1 min of PFISR signal integration. The lower panels show a sequence Poker 630 nm images for this event. In case a reader might be interested, the plasma densities along each radar beam overlaid of the images. LOS flows from available SuperDARN radar echoes are shown in the 5577 and 630 images panels, the spatial extend of the coverage shown being larger in the red line panels because of the larger spatial FOV of the 630 nm images due to their higher emission altitude (taken to 110 km for the 557.7 nm and 230 km for the 630.0 nm). Yellow arrows in the 557.7 nm insert are to illustrate flow directions inferred from the PFISR LOS flows, substorm auroral onset is identified by the white arrows, and yellow arrows in the 630 nm panels identify an equatorward moving polar cap patch. ASI, all sky imager; FOV, field-of-view; PFISR, Poker flat incoherent scatter radar; LOS, line-of-sight; THEMIS, time history of events and macroscale interactions during substorms.

fully valid. However, the direction of the vector flows is consistent with the LOS velocity. In the 0801:40 UT 557.7 nm blowup, the LOS flows indicate a flow with a strong equatorward component intruding into the poleward portion of the PFISR beams (indicated by a yellow arrow), where equatorward flow is shown by the two most poleward flow vectors. This flow then intruded all the way to the growth phase arc at the next radar measurement time (LOS flows in the 0803:07 UT 557.7 nm blowup and vectors in 0803:32 UT full mosaic). The flow was also seen by the western-most SuperDARN radar beam in the 0803:32 panel, and onset occurred during this radar measurement minute (see beading and subsequent wave growth in the 557.7 nm images in File S2 from 0803:20 to 0804:47 UT). Furthermore, the onset was first seen slightly to the west of the PFISR meridian and just where the intruding flow channel was observed. The intruding flow continued during the next measurement minute as the auroral expansion started to develop, and the flow then turned eastward. This was a thin auroral oval event, so it would be difficult to identify a streamer associated with the intruding flow channel. However, with the PFISR data, we see the flow channel very clearly heading to the onset location just before onset.

Also, as identified by the yellow arrows in the bottom row of Figure 2, a weak 630 nm feature moved equatorward from poleward of the auroral oval to near the onset longitude near the onset time. This feature is somewhat difficult to discern in the individual images of Figure 2; however, its equatorward motion can be weakly discerned in file S2. This is a possible signature of a polar-cap patch, which appears to move from the polar cap to the auroral oval as has previously seen in observations (L. R. Lyons et al., 2016; Q. H. Zhang et al., 2013) and from simulations (Crowley et al., 1996). In Figure 2, it is identified as moving ~3° in latitude is ~7 min, or ~800 m/s, which is roughly consistent with the peak LOS speeds seen by PFISR. Patches originate from the dayside cusp region (Buchau et al., 1985; Goodwin et al., 2015; Hill, 1963; Walker et al., 1999), and are carried to the nightside auroral oval by channels of enhanced flow within the polar caps (Y. Nishimura & Lyons, 2016; Nishimura, Lyons, Nicolls, et al., 2014; Zou et al., 2016; Zou, Nishimura, Lyons, Shiokawa et al., 2015). Thus, this possible observation of a patch moving to near the substorm onset region suggests that the flow channels leading to the onset may have had its origin near the dayside boundary of the polar cap.

3.2. Events 2,3: March 17, 2013, 0813:07 Onset and November 23, 2012, 0839:47 Onset

A second example (on March 17, 2013) is shown in Figure 3, with supporting information Text S3 showing the three-panel movie with full time resolution images (every ~12 s). This is a classic streamer onset event.

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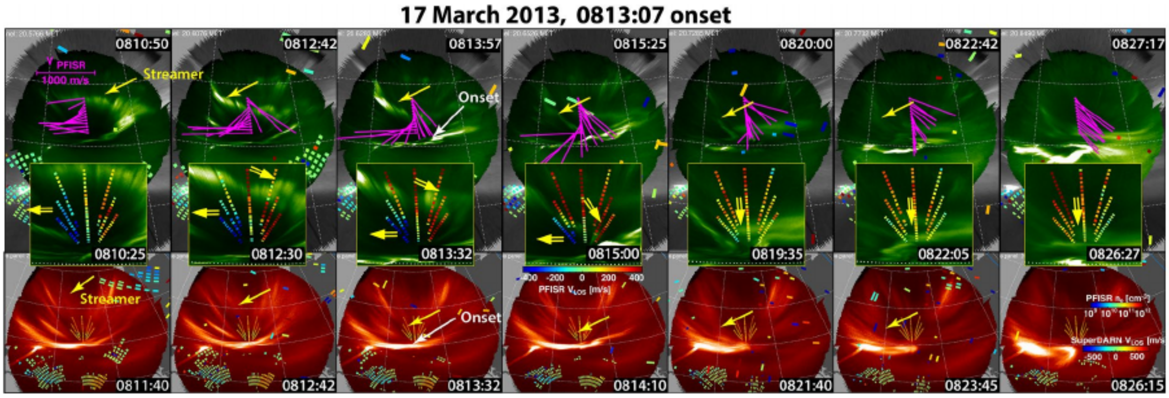

Figure 3. Observations from event 2, the March 17, 2013, 0813:07 onset, in the same format as Figure 2. Observations after onset are shown 2–5 min intervals to illustrate the extent of post-onset development.

The streamer is initially (0810:50 UT) seen in the 557.7 nm emissions with only a small equatorward tilt. The streamer then becomes increasingly tilted, and the flow channel along its poleward\eastward edge is seen clearly in both the PFISR vector and LOS flows. Westward flow of the dusk cell continues equatorward of the streamer prior to onset. During the minute when the vector and LOS flows associated with the streamer are seen reaching the growth phase arc near the equatorward boundary of the auroral oval, onset occurs along that arc. As identified in the 630 nm panels and seen in S3, a weak red line enhancement can be seen moving to near the onset location. It follows the shape and motion of the streamer seen in the 557.7 nm emissions, so it is likely the higher altitude emissions of that streamer and not a polar cap patch. The ground N component shows a ∼100 nT drop that started a few min before onset in association with the pre-onset streamer, and it then fell by up 500 nT ∼9 min later in association with expansion phase aurora. While this onset spread azimuthally across the FOV of the green line images, the activity did not expand very much poleward, so it probably should be called a pseudo-substorm. It is interesting that, as seen in both the 557.7 and 630 nm emissions, the streamer continues to be seen adjacent to the flow channel after onset, suggestion a possible relation to the driving of expansion phase activity after the onset.

The November 23, 2012 onset (Figure 4 and Text S4 in supporting information) shows similar features to the above March 17, 2013 onset. The flow turned equatorward and, as indicated by yellow arrows, the LOS flows seen by the poleward and slightly east of poleward looking radar beams moved right toward the onset longitude just prior to the onset (seen in the 557.7 nm images of S4 at 0839:47 UT). As identified in the 557.7 and 630 nm panels (shown over a longer time period preceding onset than are the 557.7 nm images), a streamer can be seen moving to near the onset location. As with the event in Figure 3, the streamer continues to be seen adjacent to the flow channel after onset. While the ground magnetometer perturbation for this event

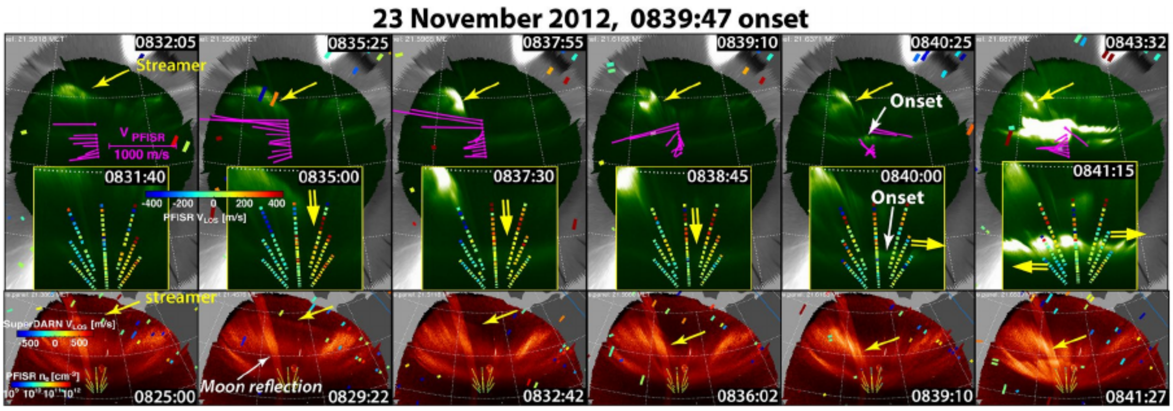

Figure 4. Observations from event 3, the November 23, 2012, 0839:47 onset, in the same format as Figure 2.

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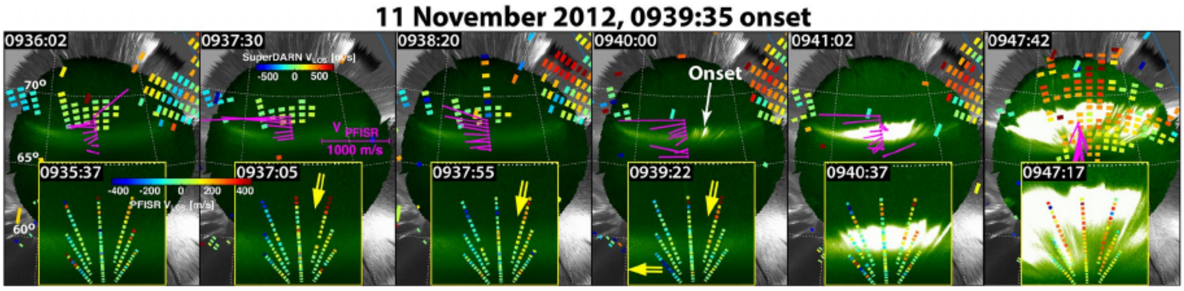

Figure 5. Observations from events 4 and 5, the March 7, 2013, 0710:37 and 0714:10 onsets, in the same format as Figure 2.

was quite small (~75 nT in S1), the expansion phase auroral activity expanded poleward a few degrees in latitude. Also, of interest to the companion paper, is the away-from-the radar LOS flows identified in the 0841:15 blowup that were seen poleward of the dawnward azimuthal expansion of brightening of the onset arc and equatorward of the duskward azimuthal expansion of that brightening.

3.3. Events 4,5: March 17, 2013, 0710:37 Pseudo and 0714:10 Onset

As shown in Figure 5 and Text S5 in supporting information, a pseudo-substorm onset at 0710:37 UT occurred just to the east of the PFISR meridian (The onset faded after ~2–3 min and was followed by the onset of full substorm at 0714:10 UT. These events were unusual in that, as can be seen in S5, an earlier streamer lead to an approximately east-west oriented arc that moved equatorward to geomagnetic latitude Λ ~65° prior to these onsets, and the onsets occurred ~2° poleward of this arc.

Flows were directed southwestward before the onsets, and then equatorward flows appeared as can be seen in both the LOS and vectors flows in the second panels, which were ~1 1/2 min prior to the first onset. As seen in the 0711:15 UT panel, enhanced equatorward LOS flows along the beams pointed along the magnetic meridian and the along next beam to the east penetrated equatorward, and as close as can be determined, to the location of the onset, which is identified in the 0710:37 UT vector flow panel. This enhanced flow to the onset location is supported by the 630 nm emissions. As indicated by the yellow arrows within the bottom row panels of Figure 5, and can be seen in S5, a patch or polar cap arc (it is difficult to distinguish between the two in this case) can be seen moving equatorward to the location and at the time of this onset. The region of enhanced LOS flows retreated poleward in the next LOS panel flow panel (0713:20 UT) and the activity from the 0710:37 UT onset faded, thus identifying this event as a pseudo-substorm.

Equatorward penetration of enhanced flows renewed in the next panel (0714:22 UT), and the flows were seen most prominently in the two radar beams looking just west of the magnetic meridian. The significantly enhanced equatorward flows can also be seen in the flow vectors in the 0714:35 UT panel, though it must be remembered that longitudinal localization of the incoming flows impacts the accuracy of the flow vector calculation. This enhanced flow to the onset location is supported by the PBI and streamer identified in the 0713:20 and 0713:45 UT panels of the 557.7 nm emissions, the streamer being in nearly direct contact with onset as seen most clearly in the 0714:10 and 0714:22 UT vector flow panels of S4. The PBI is located just above FYU, and is thus almost certainly responsible for ~200 nT depression in the ground magnetic field at FYU that developed prior to the second onset (The magnetic field depression at the more equatorward stations, DAW and CMO, are likely related to the passage of the pre-existing, more-equatorward arc over those stations, and the later depressions at BRW and DED are from expansion phase activity near the auroral poleward boundary). It seems impressive that this second flow enhancement is seen along the more western beams that appear to point to the onset, which occurred just to the west of the PFISR meridian, whereas the first onset and its associated flows occurred just to the east of the PFISR meridian.

3.4. Events 6,7, and 8: November 11, 2012, March 15, 2013, November 19, 2012

Of the nine events during the PINOT campaign with onsets within or just equatorward of the FOV of the PFISR radar, six (event 1–5 above, plus the one in Y. Nishimura, Lyons, Nicolls et al. (2014)) show clear signs

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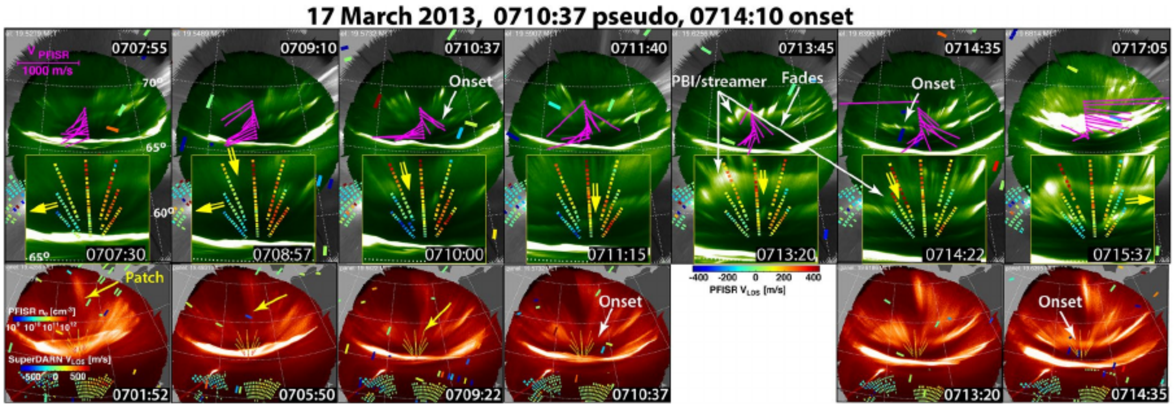

Figure 6. Observations from event 6, the November 11, 2012, 0939:35 onset, in the same format as Figure 2, except the 630 nm images are not included.

of flow channels moving equatorward to the onset location near the time of onset. Of the remaining three cases, the November 11, 2012, 0939:35 UT event is shown in Figure 6 and Text S6 in supporting information (We do not show the 630 nm images for these three cases, because we have not identified any features relevant to this study). Based on the auroral poleward expansion, this is clearly a full substorm, though the ground magnetometer depressions are very small (peak about −70 nT). Equatorward LOS flows are identified in the three LOS panels just prior to the time of the onset, and these flows are seen at the appropriated longitude to be directed toward the onset, which was just to the west of the PFISR meridian. However, flows away from the radar are seen in the first beam to the west of the meridian in the 0937:05 and 0937:55 panels, and these flows are sufficiently strong that the vector flows are directed almost westward. Only in the panel at essentially the same time as the onset (0939:22 UT) do the LOS flows away from the radar decrease and give flow vectors that turn a small amount equatorward (0940:00 UT panel). It is not possible to determine the extent to which longitudinal localization of a more equatorward directed flow channel near the longitude of onset may have affected the flow vector measurements. We did have SuperDARN echoes in a good location to see an equatorward directed flow channel, but unfortunately this region of echoes disappeared ~2 min prior to the onset. Thus, we can only say that the LOS flow measurements are consistent with the flow channel onset scenario, and we note that this consistency is supported by the location of the onset relative to the location of the equatorward LOS flows mentioned above. Also, the away from the radar LOS flows within the SAPS region that are identified in the 0939:22 UT panel are consistent with the existence of an incoming flow channel near the time of onset.

For the events on March 15, 2013 and November 19, 2012, the PFISR data do not show a flow channel leading to onset as clearly as for the previously discussed events, but we are fortunate that both have good SuperDARN echo coverage in the region surrounding the onset. To take the best advantage of this data for our purposes, we apply the technique of Bristow et al. (2016) for using SuperDARN observations to produce local maps of two-dimensional plasma flows with unprecedented spatial resolution by using the local LOS observations and the divergence-free condition. This technique results in maps having spatial resolution set by that of the underlying measurements, and the flows are only minimally influenced by a background statistical model.

Observations for the March 15, 2013, 0913:45 UT onset is shown in the upper half of Figure 7 and Text S7 in supporting information. The event had only ~1° of auroral poleward expansion after onset, and only an ~20 nT magnetic field depression was seen (at FYU and DAWS), so this is a pseudo substorm. As indicated in the 0913:45 UT and 0915:00 UT panels of Figure 7, an enhanced LOS flow was seen by PFISR coming from poleward of the visible 557.7 nm emissions and pointing toward the onset. However, this flow did not appear as an equatorward flow in the vector flows. On the other hand, the SuperDARN LOS flows in the 0912:42, 0913:30, and 0914:42 UT panels of Figure 6 show a region of enhanced toward the radar (equatorward) LOS flows that moves westward with time toward the onset longitude. These flows are seen quite clearly in the flow vectors, which are given every 1 min (the radar measurement cadence) in the lower portion of the March 15, 2013 portion of Figure 7. As demarcated by the curved arrow, the initiation of an

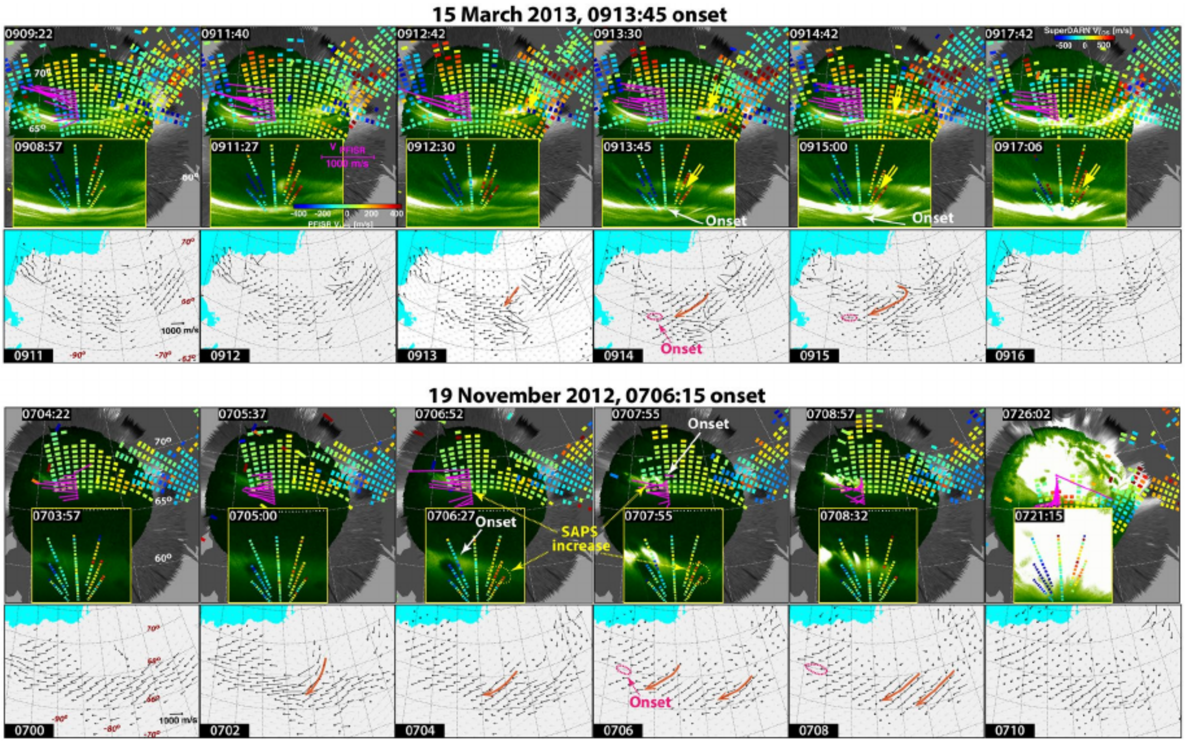

Figure 7. Observations from events 7 and 8, the March 15, 2013, 0913:45 and November 9, 2012, 0706:15onsets, in the same format as Figure 2, except the 630 nm images are not included. The bottom row for each event shows two-dimensional plasma flows obtained from the local LOS observations and the divergence-free condition using the Bristow et al. (2016) technique and the measurement time cadence (1 min for March 15, 2013, 2 min for November 9, 2012).

observable equatorward flow channel is seen in the 0913 UT panel, and, as seen in the 0914 UT panel, this flow channel then extended equatorward and westward with its leading edge pointed almost directly at the onset at the onset time. The 0915 UT panel shows the flows to the onset region continuing, as well as their possible connection to a flow channel from the polar cap crossing the the auroral poleward boundary at ~68° magnetic latitude.

Observations for the November 19, 2012, 0706:15 UT onset are displayed in the lower portion of Figure 7 and Text S8 in supporting information. This onset led to a full substorm, and, as with previous events, there was little magnetic perturbation with the onset but substantial ground N depressions (~-300 nT) about 10 min later in association with expansion phase streamers. Unlike for all the previously discussed events, PFISR did not see evidence for an equatorward flow enhancement leading to the onset, and for this event, there was a broad region of SuperDARN echoes that would likely have seen such a flow channels if it existed. However, based on L. R. Lyons et al. (2010) and Y. Nishimura et al. (2010), we expect some events to not be associated with the direct impact of a equatorward directed flow channel, but instead to be associated with enhanced westward flows reaching the onset location within the SAPS region. Even prior to the onset, the SAPS flows for this event were stronger than during the previous two events where the aurora was sufficiently poleward for SAPS flows to be seen by PFISR (November 23, 2012 in Figure 4 and the November 11, 2012 event in Figure 6). Then, during the 1-min radar measurement that included the time of onset, and as indicated by dashed yellow arrows, the easternmost looking PFISR beams (0706:27 UT panel) and the vector observations (0706:52 panel) show a roughly 200 m/s increase in the SAPS flows. While the flow enhancement is not as clear as in the two events in L. R. Lyons et al. (2010), the observations show evidence for a SAPS flow enhancement at a time appropriate for the onset to have been triggerred by the westward expansion of a bubble just poleward of the onset.

The SuperDARN radar beams at the longitude of onset are directed almost along the magnetic meridian, and thus LOS flows could not detect an enhancement in SAPS speeds. However, the beams directed further to the east show strong LOS flows. Time resolution is limited to 2 min for this event due to the 2 min measurement cadence. When coverted to two-dimensional flows using the Bristow et al. (2016) technique (bottom panels in Figure 7), we see strong ~1 km/s SAPS flows prior to the onset. This reflects the change in the sign of the LOS flows from the more western looking to the more eastern looking beams. Then, starting in the 0702 panel (reflecting data from 0701 to 0703 UT), we see far more equatorward directed flow channels as indicated by the curved arrows in the 0702 and subsequent panels. These flows can be seen to reach into the SAPS region equatorward of the substorm onset, where they turn toward the west and toward the onset longitude. While these flows are just what is expected for a flow channel to bring reduced entropy plasma to the onset region, we cannot verify this because we do not see enhanced SAPS flows reaching the onset longitude as indicated by the PFISR observations. This could be a result of the low time resolution for this event and/or the poleward orientation of the beams, but the observations do not allow determination of whether this is the case. Thus we can only conclude that there is evidence for the azimuthal expansion of an intruding bubble, but the evidence is not definitive.

4. Summary and Conclusions

The concept of flow channel triggering of a substorm onset in the inner plasma sheet was proposed by Nishimura et al. (2010) using observations of auroral streamers from ASIs. While this idea has received strong support from auroral observations, auroral observation have limitations due to auroral viewing conditions and that streamers may not be seen to directly contact the onset location due to the azimuthal spreading of reduced entropy plasma by magnetic drift. However, it is not the aurora, but is the intrusion of reduced entropy plasma to the onset region that is proposed to lead to onset. Such plasma moves equatorward due to interchange motion until it reaches the inner plasma sheet, where it spreads azimuthally, its duskward expansion being due to magnetic drift. Both the equatorward motion and its duskward expansion can be seen in plasma flows that map to the ionosphere. Equatorward flows can be seen within the ionospheric mapping of the earthward moving low entropy plasma. After its earthward motion ceases within the inner plasma sheet, westward flow should be seen equatorward of the inner boundary of the duskward expanding low entropy plasma (It should also be seen by flows poleward of the dawnward expanding low entropy plasma, see Wang et al. [2018] and companion paper.)

We have identified nine events (including the one in Nishimura, Lyons, Nicolls et al., 2014) with a substorm auroral onset within the FOV of the Poker ASI 557.7 nm observations and within or just equatorward of the latitudinal coverage of the PFISR beams. Focusing on what triggers onset, we include both onsets that expanded poleward to a full substorm and those with limited poleward expansion (i.e., pseudo-substorms). Remarkably, for seven of the nine events, PFISR shows enhanced LOS flows with an equatorward directed component that appears to be directly heading to the onset location at a time appropriated for given rise to the onset. For five of the six of these events analyzed here, we also clearly see the flows leading to onset in the two-dimensional flow vectors calculated under the assumption of longitudinal flow invariance. In four of these cases, this is seen as a substantial equatorward turning of the flow, and for the fifth event, which occurred 3.5 min after a previous pseudo onset, it is seen as an enhancement of the equatorward flow.

Neither of the two remaining events showed an equatorward turning in the PFISR flow vectors. For the March 15, 2013 event, there is some evidence for an incoming flow channel in the PFISR LOS flows. However, due to the excellent SuperDARN echo coverage for this event, we were able to obtain flow vectors from the SuperDARN data via the divergence-free condition. Those vectors clearly show an equatorial turning of the flows associated with a flow channel that appears to come into the auroral oval from the polar cap and be bringing new plasma to the onset location at the time of onset. The November 19, 2012 event is different from the other in that we see no evidence for a flow channel moving equatorward to the onset location. Instead, we see evidence in the PFISR observations of SAPS flows for this onset to have been associated with the duskward expansion of the bubble. We were again fortunate with the coverage of SuperDARN echoes for this event, and the resulting flow vectors show evidence for one or more flow channels penetrating into the SAPS region east of the onset at a time appropriated for the onset to have been triggered by duskward expansion of a reduced entropy plasma bubble. However, the SAPS regions flow enhancement seen by PFISR near the onset longitude is not seen in the SuperDARN flow vectors, this possibly being a result of the SuperDARN beams being perpendicular to the westward SAPS flows.

Though only a total of 11 cases have been examined so far (the 8 here, the one in Y. Nishimura, Lyons, Zou et al. [2014]) and the four in L. R. Lyons et al. (2010), there are clear observations of flow channels leading to onset in the large majority of these cases and some evidence in the remaining cases. This supports the proposal that substorm onset is due to the intrusion of new plasma to the onset region. The flux tube integrated entropy of this new plasma must be lower than that of the surrounding plasma, and so the new plasma must change the entropy distribution within the inner plasma sheet. It appears plausible that this entropy distribution change is important for the substorm onset instability that is seen via the growing auroral and electric waves seen with substorm auroral onset.

We have also seen some evidence for patches moving toward the onset location at time of onset for two of our events, and possible connection to a polar cap flow channel for another event. These observations support the previously observed and modeled proposal (Nishimura, Lyons, Nicolls et al., 2014; Nishimura, Lyons, Shiokawa, et al., 2013; Nishimura, Lyons, Xing, et al., 2013; Nishimura, Lyons, Zou et al., 2014; Y. Nishimura & Lyons, 2016) that the flow channels leading to onset move across the polar cap following their origin near the dayside boundary of the polar cap. Also, consistent with what we have seen previously (Lyons, Nishimura, Donovan et al., 2013), substantial ground magnetic depressions associated with substorm are not seen with substorm onset but are instead seen a few to several min later in association with expansion phase streamers.

Data Availability Statement

The authors thank all participants in the worldwide SuperDARN collaboration for the distribution of SuperDARN data via http://vt.superdarn.org/tiki-index.php?page=Data+Access. We thank the SuperMAG, PI Jesper W. Gjerloev for making the ground magnetic field data use here available via the SuperMAG at http://supermag.jhuapl.edu/. The data we have used here are from THEMIS, CARISMA (Mann et al., 2008), the University of Alaska, and USGS (https://www.usgs.gov/natural-hazards/geomagnetism/science/observatories?qt-science_center_objects=0#qt-science_center_objects). The University of Alaska ASI data are available from http://optics.gi.alaska.edu/optics/, and the THEMIS ASU data from http://themis.ssl.berkeley.edu/themisdata/. The PFISR data are available at amisr.com/database and isr.sri.com/madrigal. All data are properly cited and referred to in the reference list or in the acknowledgments.

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