Relations between multiple auroral streamers, pre-onset thin arc formation, and substorm auroral onset

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[1] Recent ground-based imager observations have provided evidence of precursor auroral activity leading to substorm auroral onset, where the precursor is initiated by a poleward boundary intensification (PBI) followed by an auroral streamer moving equatorward toward the onset latitude leading to substorm auroral onset. However, since many streamers do not lead to substorms, the question arises as to what conditions are required for streamers to lead to onset. Using 382 events detected by the THEMIS all-sky imagers during 2007–2009, we examined the properties of latitudinally thin, quiet arcs that eventually break up during the substorm auroral onset and the relationship of such quiet arcs to streamers. We found that a pre-existing latitudinally thin quiet arc that leads to auroral onset is much brighter than prior thin arcs that do not lead to onset, and that streamers that do not lead to onset form or intensify such quiet arcs. The newly formed or intensified quiet arc remains bright for a few to tens of minutes (~20 min on average) until a subsequent streamer leads to substorm auroral onset along the pre-existing arc. The pre-onset sequence proposed here suggests that both types of streamers, which do and do not lead to substorms, enhance auroral luminosity near the equatorward boundary of the oval, and that a sufficiently intense, quiet time thin arc near the poleward edge of proton precipitation, likely corresponding to a large plasma pressure gradient in the near-Earth plasma sheet, reflects important pre-conditions for a precursor flow burst to trigger substorm auroral onset.

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1. Introduction

[2] Deployment of the ground-based all-sky imager (ASI) array of the THEMIS project [*Angelopoulos*, 2008; *Mende et al.*, 2008] has been providing remarkable large and meso-scale auroral views in high spatial and temporal resolution. One of the most notable findings through the imager network observations is the sequence of events leading to substorm auroral onset [*Kepko et al.*, 2009; *Nishimura et al.*, 2010a; *Lyons et al.*, 2010a]. While the pre-onset time sequence has been a topic of long-standing debate [e.g., *Ohtani*, 2004], the ASI measurements showed a distinct auroral streamer (also called north–south auroral form) propagating equatorward, leading to substorm auroral onset. Such a streamer tends to originate from a poleward boundary intensification (PBI), and the pre-onset PBI and streamer sequence is commonly observed in many events where available imagers cover a wide area of the auroral zone [*Nishimura et al.*, 2010a]. The streamers reach the near-Earth plasma sheet just prior to substorm auroral onset and trigger onset instability, which abruptly releases energy stored during the growth phase [*Lui and Burrows*, 1978]. Onset sometimes occurs near where the streamer reaches the equatorward portion of the auroral oval, but often occurs after the pre-onset streamer luminosity turns from moving equatorward to moving azimuthally to the onset location. Furthermore, contrary to bright streamers frequently observed during magnetically disturbed times, the pre-onset auroral sequence with dimmer and localized streamers is observed prior to isolated substorms as often, and with similar characteristics, as for substorms that follow other activity [*Nishimura et al.*, 2010b, 2010c]. Such faint and localized streamers could have been missed by space-based imaging, and thus high spatial and temporal resolution of the imager array is particularly important for detecting such pre-onset auroral forms [*Mende et al.*, 2011].

[3] PBIs are believed to be associated with enhanced localized magnetic reconnection. Auroral streamers are the

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ionospheric projection of upward field-aligned currents forming on the western edge of earthward flow bursts in the plasma sheet [*Lyons et al.*, 1999; *Sergeev et al.*, 2000; *Nakamura et al.*, 2001] that suggest earthward-moving bubbles with reduced entropy content [*Chen and Wolf*, 1999; *Sergeev et al.*, 2000; *Nakamura et al.*, 2001], and such transient plasma flow enhancements play an important role in plasma sheet transport [*Angelopoulos et al.*, 1994]. Thus the pre-onset auroral sequence has provided strong evidence that enhanced magnetic reconnection initiates prior to onset, as has been inferred from in situ observations [*Angelopoulos*, 2008], and that the ensuing intrusion of new plasma to the near-Earth plasma sheet leads to the substorm onset instability. It is important to note that streamers and flow bursts occur under a variety of magnetic conditions, and many of them do not lead to auroral onset. For example, bright streamers tend to emerge during the substorm expansion and recovery phases and evolve into diffuse aurora enhancements near the equatorward boundary of the oval without an additional auroral onset [*Nakamura et al.*, 1993; *Henderson et al.*, 1998]. This leads to the important question of what conditions are necessary for a streamer to lead to substorm auroral onset.

[4] *Nishimura et al.* [2010b] examined an isolated substorm auroral onset that was preceded by four observed auroral streamers. The first three of these disappeared without onset but the last streamer led to onset. They found a difference in intensity of a pre-onset, latitudinally thin arc located near the auroral equatorward boundary. The thin quiet arc was much brighter at the time of the last streamer than during the preceding streamers, while the streamer property was essentially the same. Interestingly, while the preceding streamers did not lead to onset, they led to small intensifications of the thin arc. Since auroral arcs can be connected by upward field-aligned currents to pressure gradients [e.g., *Galperin et al.*, 1992], this multiple streamer sequence suggests that all of the streamers contribute to accumulate enhanced plasma pressure or to increase its gradient in the near-Earth plasma sheet, and that onset instability can be triggered when the pressure gradient becomes sufficiently high. Such an enhanced pressure gradient just before substorm onset has been deduced from enhanced azimuthal flows [*Nishimura et al.*, 2010b] and has also been directly measured in association with precursor thin arcs [*Xing et al.*, 2011]. It should be noted, however, that the result on the multiple streamer sequence by *Nishimura et al.* [2010b] was based only on a single event, and therefore a further analysis using a larger number of events should be conducted to evaluate if the sequence described above is common for substorms.

[5] Substorm auroral onset often occurs along such a pre-existing azimuthally elongated thin arc, which can thus be considered as an onset precursor [*Deehr and Lummerzheim*, 2001; *Kadokura et al.*, 2002; *Lyons et al.*, 2002; *Donovan et al.*, 2006; *Lessard et al.*, 2007; *Liang et al.*, 2008]. It emerges a few to tens of minutes prior to onset and stays dim and quiet generally poleward of the most intense proton precipitation. Auroral onset tends to occur along the same arc and is identified by quasiperiodic beading along the arc [*Voronkov et al.*, 1999] followed by rapid intensification and poleward expansion. While such a thin arc has been understood to be of importance in determining the location of substorm onset, only limited attention has been given to the sequence leading to this thin arc.

[6] In the present study, we use individual event and statistical analyses to investigate whether a thin arc is a common feature prior to onset and to determine its relation to pre-onset auroral streamer sequences that do and do not lead to substorm auroral onset. We use 382 events obtained by the THEMIS ASIs between November 2007 and April 2009. We find that, in most cases, onset occurs when a pre-existing thin auroral arc is located near the equatorward boundary of the auroral oval at the time of streamer formation. We also find that such an arc is not present, or is relatively weak, at the time of auroral streamers that do not lead to onset. Such streamers, however, are found to lead to formation or small intensification of the thin arc, which stays for a few to 10s of min and breaks up when the following streamer propagates toward the thin arc. We suggest that an enhanced plasma pressure gradient in the near-Earth plasma sheet in addition to an intruding streamer is an important condition to lead to substorm onset, although, due to variable sky conditions and limited in situ satellite coverage, the present study does not determine a threshold of arc intensity or plasma pressure.

2. Case Study

[7] We show pre-onset sequences of three isolated substorms in this section. Substorm auroral onset of the first event occurred at ~1110 UT on 28 February 2008. The imager sequence is shown in Figures 1a–1f and Movie S1 in the auxiliary material.[1] The interplanetary magnetic field (IMF), auroral keograms, and ground magnetometer data are shown in Figures 1g–1l. The IMF B_z turned southward at ~1006 UT (Figure 1g), and the poleward boundary of the auroral oval started to be active immediately after that (Figure 1h). The auroral oval started to drift equatorward at ~1020 UT. The auroral activity was initially low at the equatorward portion of the auroral oval, which mainly consisted of diffuse aurora (Figure 1a and i) and the THEMIS *AL* index was only slowly varying and stayed above −200 nT, indicating that the auroral activity prior to the onset remained weak throughout the North American sector.

[8] A PBI formed at ~1040 UT (Figures 1a and 1h, poleward-most intensification reaching >~3000 count/s) and led to an auroral streamer propagating equatorward (Figures 1b and 1i). This streamer disappeared without leading to substorm auroral onset. Instead, a latitudinally thin arc formed right after the streamer, near the poleward edge of the pre-existing diffuse aurora that extended longitudinally near the equatorward boundary of the oval (Figures 1c and 1i). This thin arc was much fainter than the following onset intensification (Panel i is given in log scale), and stayed quiet for ~25 min until the onset time. In addition, magnetic perturbation associated with this arc was small and only changed gradually. These facts indicate that the thin arc formation was not the onset of auroral expansion or a pseudo-breakup, but was part of the pre-onset sequence of events that occurred near the end of the growth phase.

[9] The final pre-onset streamer propagated toward the equatorward boundary at ~1108 UT (Figures 1e, 1f and 1i). The intensity and equatorward propagation speed (slope of

[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/ja/2011ja016768.

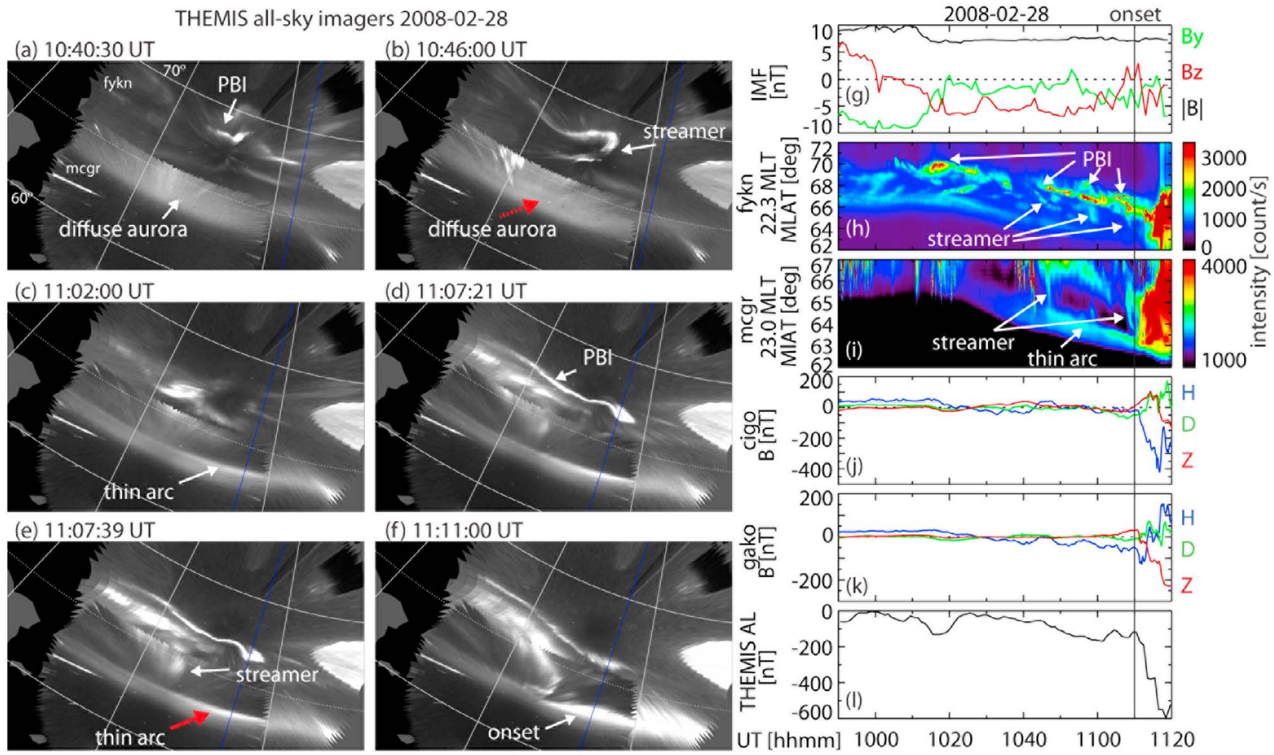

Figure 1. Pre-onset sequence of an isolated substorm occurring on 28 February 2008. (a–f) Snapshots of THEMIS ASI data. The pre-onset thin arc is highlighted by the red solid arrow. White lines are isocontours of magnetic latitude (every 10° in solid lines) and longitude (every 15°). The blue line shows the magnetic midnight meridian. The whole sequences are shown in Movie S1. (g–l) IMF, keograms and magnetometer data. The vertical line marks the onset time. MLTs at the central times of each keogram are shown in the labels. The intermittent intense emissions above 64° MLAT until 1042 UT in Figure 1i are light contamination. The intensity in Figure 1i is given in the log scale. The MLAT and magnetic longitude (MLON) at Fort Yukon (FYKN), Mcgrath (MCGR), College International Geophysical Observatory (CIGO) and Gakona (GAKO) are (67.24°, 266.14°), (61.72°, 259.84°), (65.06°, 265.26°) and (63.06°, 269.02°).

the streamers) shown in Figure 1i is essentially the same as for the preceding streamer. A major difference from the previous sequence is, however, existence of the bright pre-onset thin arc located near the equatorward boundary of the oval (Figures 1e and 1i). The streamer led to auroral onset when the streamer reached just poleward of the pre-existing thin arc. The auroral onset occurred along the pre-existing thin arc at ~1110 UT (vertical line) as marked by rapid auroral intensification followed by poleward expansion and an auroral electrojet enhancement indicated by sudden change in the ground *H* component at stations near the onset location (Figures 1j and k) and *AL* (Figure 1l).

[10] Figure 2 presents the pre-onset sequence of the ~0504 UT, 7 March 2008 auroral onset. The whole imager sequence is given in Movie S2. The IMF was directed weakly southward during this time interval. While the poleward boundary of the auroral oval stayed active possibly due to the continuous solar wind energy input, showing multiple intensifications at ~72° magnetic latitude (MLAT) in Figure 2h, auroral activity near the equatorward boundary (Figure 2i) was quiet until the onset time. This feature can also be seen in Figure 2a. The THEMIS *AL* index (Figure 2l) stayed above −20 nT prior to the onset.

[11] Two auroral streamers propagated from PBIs toward the equatorward boundary, as indicated in Figure 2i. While the first streamer originated from the PBI shown in Figure 2a disappeared without leading to substorm onset (Figures 2b and 2i), a faint latitudinally thin arc formed at ~67° MLAT near the equatorward boundary right after the arrival of the streamer and stayed quiet for a few minutes (Figures 2c and 2i). Similar to the previous event, the thin arc intensity was much fainter than the following breakup arc (note the log scale of the color axis in Figure 2i), and the intensity was kept roughly constant until the onset time. The magnetic perturbation associated with this arc was negligibly small. As with the previous event, these features indicate that the thin arc formation is not an onset or pseudo-breakup but belongs to the pre-onset sequence.

[12] A similar sequence of a PBI and streamer repeated after the thin arc formation. The second PBI (Figure 2d) and streamer (Figure 2e) occurred almost at the same location, and with about the same size, speed and luminosity as the first streamer. Unlike the previous streamer sequence, the thin arc was present near the equatorward boundary at this time, and the streamer led to auroral onset when the streamer reached just poleward of the pre-existing thin arc. This thin

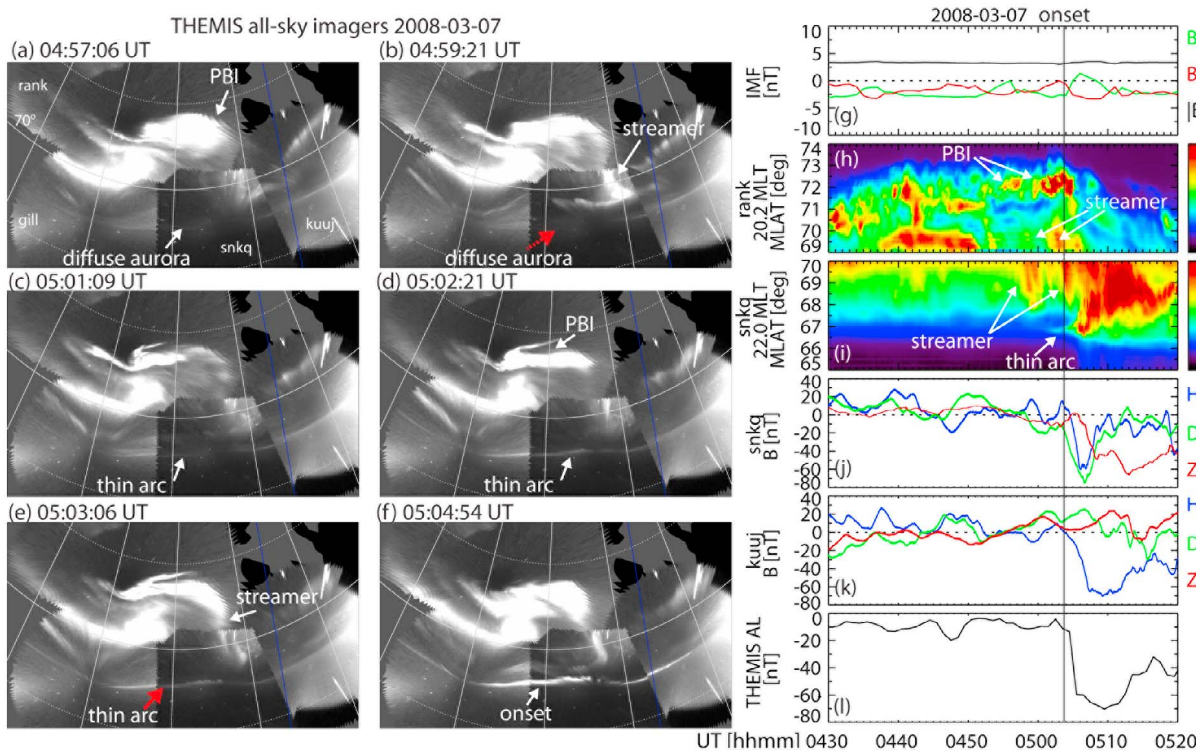

Figure 2. Same as Figure 1 but for the 7 March 2008 event. The intensity in Figure 2i is given in the log scale. MLAT and MLON of Rankin Inlet (RANK), Sanikiluaq (SNKQ), and Kuujjuaq (KUUJ) are (72.41°, 335.74°), (66.45°, 356.99°) and (66.89°, 13.23°).

arc extended over 4 h of MLT roughly along a constant magnetic latitude contour. The auroral onset occurred along the pre-existing thin arc at 0504 UT (vertical line) as marked by rapid auroral intensification followed by poleward expansion and an auroral electrojet enhancement indicated by decrease in the *H* component and THEMIS *AL*.

[13] These two cases show multiple auroral streamers with essentially the same property. The only identified difference between the conditions just before the streamers that did and did not lead to substorm auroral onset is the existence of the latitudinally thin arc at the time of the onset-related streamer. However, the streamers that did not lead to onset led to formation or intensification of the thin arc. Based on the link between fast flows in the plasma sheet and auroral streamers [e.g., *Sergeev et al.*, 2000], this sequence suggests that the flow bursts in the plasma sheet corresponding to each auroral streamer enhances the plasma pressure and/or its gradient in a narrow *L*-shell range in the near-Earth plasma sheet, intensifying an upward field-aligned current, which is detected as a thin arc. The brighter thin arc just before auroral onset suggests that the pressure gradient prior to the onset is sufficiently high for substorm onset instability to be initiated by the onset-related flow burst, while the pressure gradient is too small for onset instability when a thin arc is dimmer or absent and more flow bursts could increase the pressure gradient.

[14] Another type of pre-onset auroral sequence is given in Figure 3 for the 0953 UT, 1 February 2008 substorm auroral onset. This event has already been documented by *Lyons et al.* [2010b], and thus we only briefly describe the event sequence and focus on evolution of the pre-onset thin arc. The IMF turned southward at ~0840 UT, and the diffuse-appearing growth phase auroral region started to move equatorward as in the event shown in Figure 1. The poleward boundary progressed equatorward more rapidly than the equatorward boundary (Figure 3h), leading to a narrow auroral oval at the end of the growth phase. A PBI occurred at ~0930 UT (Figures 3d and 3h), followed by a streamer (Figures 3e and 3i). While the THEMIS *AL* index had a brief excursion associated with the PBI, this is not an onset of substorm or pseudo-breakup because the magnetic perturbation was detected near the poleward boundary of the oval (FYKN) and the equatorward portion of the oval remained quiet.

[15] The faint streamer propagated equatorward and led to auroral onset along a pre-existing thin arc at the time of the vertical line. This event might be called a pseudo-breakup due to the small *AL* decrease, though the activity expanded poleward to the poleward boundary of the narrow auroral oval that existed at this time. A difference from the above two events is that the pre-onset thin arc was not preceded by an auroral streamer, but instead gradually emerged along the poleward edge of the diffuse auroral region soon after the southward turning of the IMF (Figures 3b and 3j). After the arc formation, the thin arc slowly drifted equatorward and stayed quiet until the onset time, extending over 3 h MLT.

[16] This auroral sequence appears to be similar to the higher latitude arc contacting the proton aurora shown by *Oguti* [1973], and the fast equatorward moving (FEM) arc

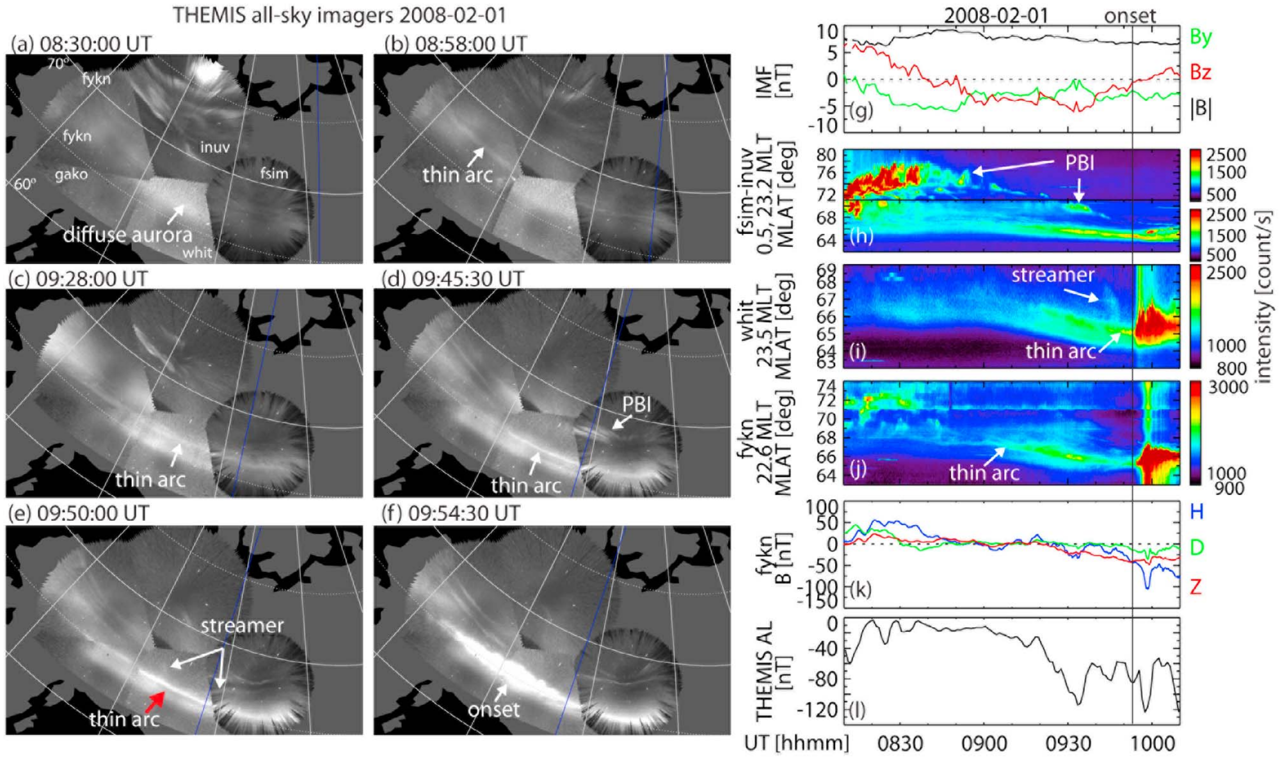

Figure 3. Same as Figure 1 but for the 1 February 2008 event. The intensity in Figures 3i and 3j is given in the log scale. Keograms from Fort Simpson and Inuvik are combined and shown in Panel h. MLAT and MLON of Fort Simpson (FSIM), Inuvik (INUV), White Horse (WHIT) are (67.30°, 293.85°), (71.23°, 275.09°) and (63.66°, 278.14°).

shown by *Kadokura et al.* [2002], though their observations were not sufficient to detect the complete sequence including the pre-onset streamers leading to onset. Although the thin arc formed without a preceding streamer, its formation soon after the IMF southward turning may suggest that large-scale enhanced convection, in addition to meso-scale transient flows as shown in the previous two events, can also contribute to increasing the plasma pressure and its gradient in the near-Earth plasmas sheet sufficiently for an ensuing streamer to lead to substorm auroral onset.

3. Statistical Analysis

[17] To evaluate if the sequences shown above are common for substorm auroral onset, we perform a statistical study in this section. We surveyed 382 events obtained between November 2007 and April 2009 and determined if a pre-onset thin arc was identifiable in each event, and when this occurred, if the thin arc formed in association with a preceding streamer. The event list is an extended version of that used in our previous study [*Nishimura et al.*, 2010a] and is provided as Data Set 1 in the auxiliary material. All of the events are used in the results shown in Figure 4, while only isolated events are selected for Figure 5. Here we follow the same criteria for selecting isolated events as used in our previous study [*Nishimura et al.*, 2010c] that isolated events are defined as onset events that occurred more than 30 min after a previous onset and did not have active auroral forms near the onset location.

[18] The events were first divided into two categories according to existence of pre-onset aurora that evolves into an onset arc. Here a pre-existing aurora is defined as aurora that stays dim and quiet after its formation and until an onset time, while an onset occurring without such an arc refers to rapid, roughly monotonic intensity increase of a new arc emerging from the diffuse aurora background. We find an occurrence probability of pre-existing auroral events (Figure 4a) of 86.7%. This tendency for onset arcs to occur along pre-existing aurora rather than being a newly formed more isolated arc is consistent with previous findings [e.g., *Deehr and Lummerzheim*, 2001]. Figure 4b shows that the percentage of pre-existing aurora events where the pre-existing aurora was a latitudinally thin arc is 90.9%, where thin has been defined as less than 30 km in width (see Figure 7 for more detail). The thinness of the arc may suggest that only a limited *L*-shell range of the magnetosphere is the source region of the precipitation leading to the pre-onset arc.

[19] The thin arc events were further examined to see if they were associated with preceding streamers (Figure 4c). We excluded events where thin arcs formed outside the available imager field-of-views (FOVs) and propagated into FOVs and where thin arcs originated from breakup arcs of preceding substorms. We find that a majority of the thin arc events (76.4%) were preceded by a streamer that formed or weakly intensified a thin arc. These cases are like the first two events in the previous section, showing thin arc formation in association with a preceding streamer that does not lead to onset.

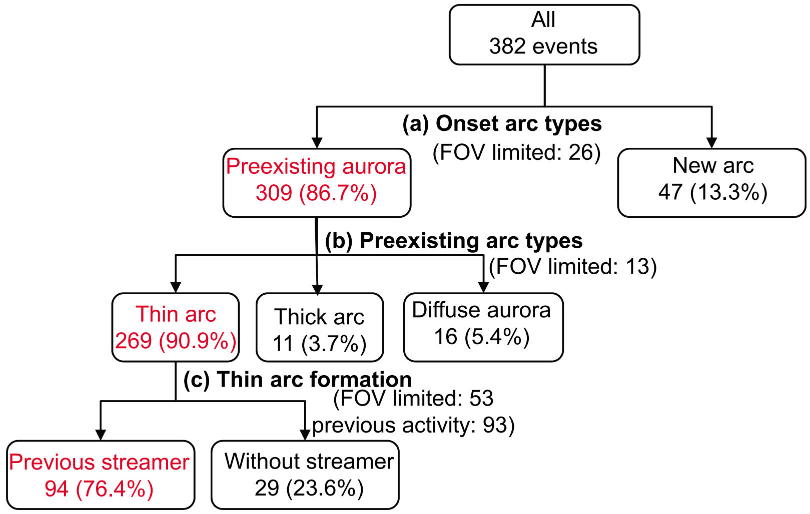

Figure 4. Number of events and occurrence probability of pre-onset thin arcs and streamers that lead to the thin arcs. All onset events are included. (a) Onset events are divided into two types, where onset occurs on a pre-existing aurora or a new arc. (b) Pre-existing aurora events are further classified into three according to the arc thickness, thin (<30 km), thick (>30 km) and diffuse (unstructured). (c) The thin arc events are examined if associated with a preceding streamer. Events where a thin arc originated from previous substorm-type activity (93 events) were excluded. Events without sufficient FOV to detect each auroral feature or with severe light contaminations are marked as "FOV limited," and not used in the statistics.

[20] On the other hand, the rest of the events in Figure 4c are not associated with streamers, as shown in Figure 3. While this type of sequence is found to be less common than the streamer-related thin arc sequence, such a sequence leading to a pre-onset thin arc may be related to enhanced large-scale convection during the growth phase slowly building up a pressure gradient in the near-Earth plasma sheet. This is supported by the gradual equatorward motion of the thin arc seen in Figure 3, which averages ~1° MLAT between the times of arc formation and the onset. We should note, however, that initiation of a faint thin arc may not be precisely determined due to diffuse aurora background, especially for events with bright diffuse aurora. Thus the occurrence probability of thin arcs without streamers might be smaller than that shown here. The diffuse aurora background could also be a reason for some of the events in the low probability categories (marked by black) of Figure 4a and 4b, because a faint thin arc might be obscured by diffuse aurora.

[21] We also performed the same analysis for isolated substorms and show the results in Figure 5. All the occurrence probabilities can be seen to be essentially the same as in Figure 4, indicating that the results described above are common for both isolated and multiple-onset substorms.

[22] Figure 6 shows the time differences between pre-onset thin arc formation and auroral onset. In spite of large

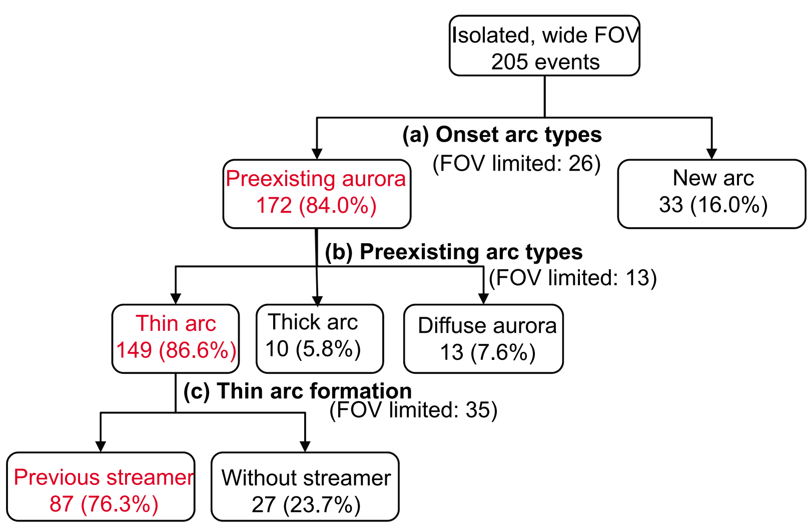

Figure 5. Same as Figure 4 but for isolated events.

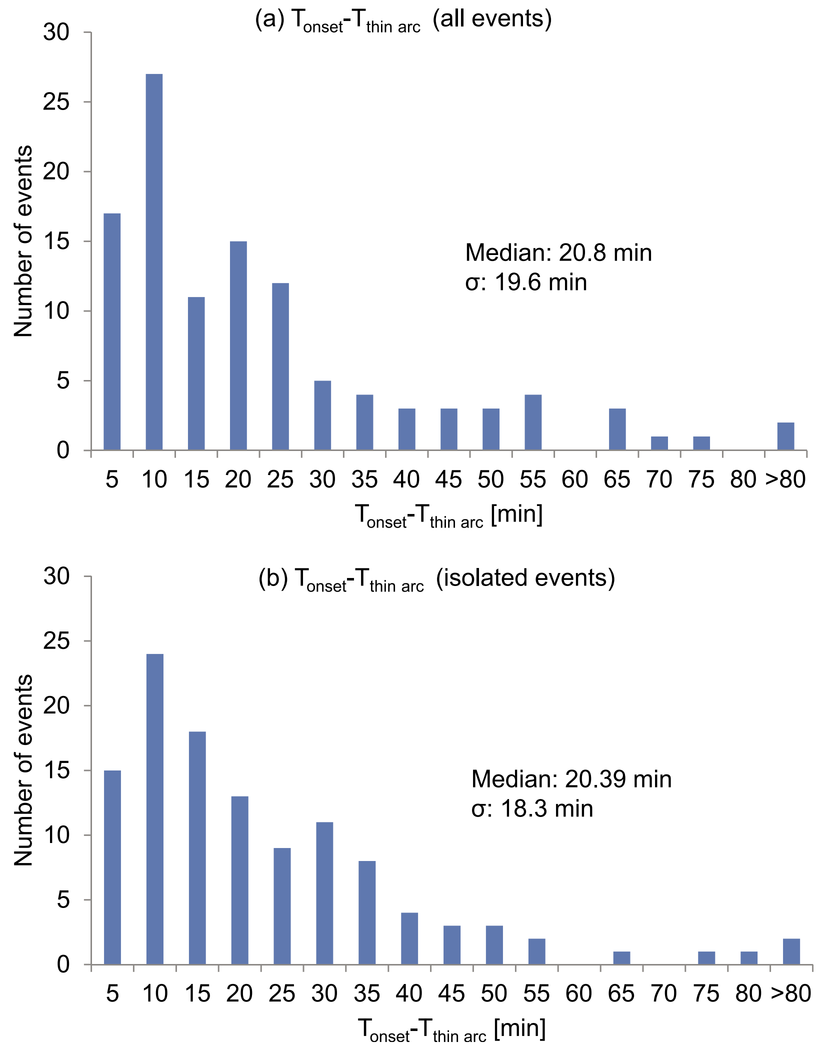

Figure 6. Time difference between pre-onset thin arc formation and substorm onset. (a) All onset events included and (b) isolated substorms.

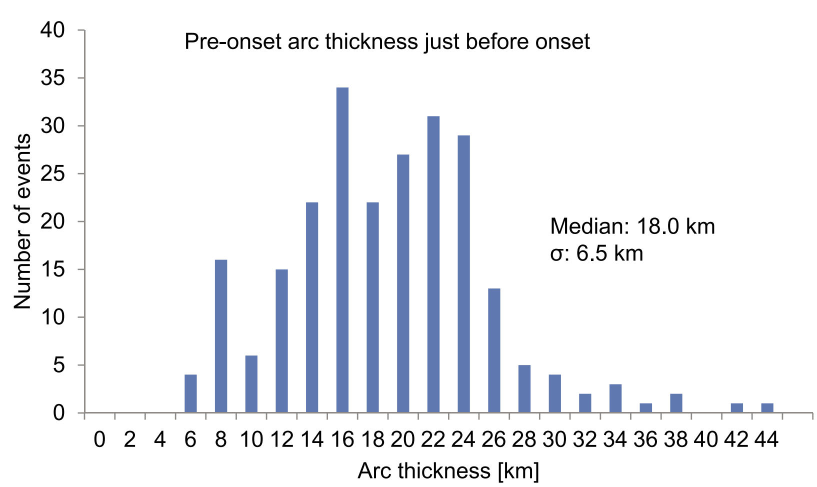

Figure 7. Distribution of the pre-onset arc thickness just before onset, assuming mapping at 110 km altitude.

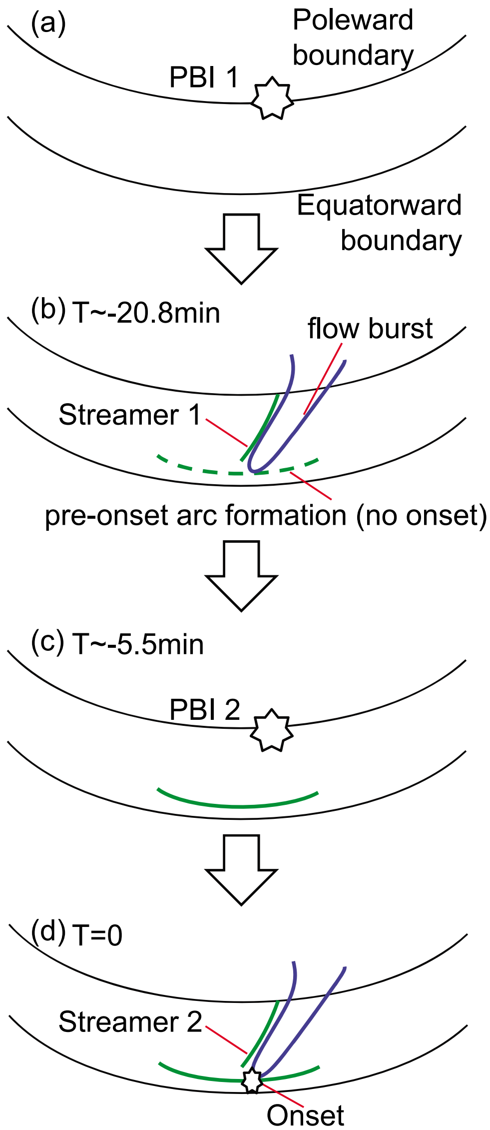

Figure 8. Schematic illustration of the pre-onset auroral sequence found in this study. (a) A PBI initiates when the equatorward boundary is quiet and dominated by diffuse aurora. (b) The PBI is followed by an auroral streamer propagating equatorward and leading to the pre-onset thin arc. This would be associated with a plasma flow channel associated with an enhanced flow speed located to the east of the streamer. Substorm onset does not occur at this moment but the thin arc stays quiet. (c) Another PBI occurs when the thin arc is present near the equatorward boundary. (d) A streamer propagates equatorward in a similar way to Figure 8b. Substorm auroral onset occurs along the pre-existing thin arc near the steamer meridian (the streamer sometimes continues drifting eastward or westward and an onset occurs away from the contact point to the growth phase arc) when the streamer reaches near the pre-existing arc.

standard deviations, the median time difference is ~20 min for both all (Figure 6a) and isolated (Figure 6b) events, indicating that a pre-onset thin arc typically forms in association with a preceding streamer, and then stays for ~20 min until the onset initiated by the following streamer. This time interval is similar to the typical repetition period of flow bursts in the plasma sheet and PBIs [*Lyons et al.*, 1999], consistent with the pre-onset arc strongly controlled by transient plasma sheet dynamics.

[23] Finally, a distribution of the pre-onset arc thickness just before auroral onset is shown in Figure 7. The number of events is 238, where pre-onset arcs were detected within 45° from the zenith by one of the available imagers and where arc shape can be clearly determined. While it is difficult to estimate widths of tall auroral curtains seen during active times, the latitudinally thin quiet arcs typically do not show such tall structures as shown in Figures 1–3. This feature allows us to estimate the latitudinal width away from the zenith. Most of the events have thickness less than 30 km as shown in Figures 4 and 5, and the median thickness is 18.0 km. This arc width is similar to the thickness of stable arcs [*Kim and Volkman*, 1963; *Knudsen et al.*, 2001].

4. Discussions and Conclusions

[24] Taking advantage of the unprecedented coverage and resolution of the THEMIS ground-based ASI array data, we have investigated a condition to lead to substorm auroral onset associated with multiple pre-onset streamers. We found based on case and statistical studies that a thin growth phase arc just before onset is much brighter than at times of preceding streamers, while the characteristics of the multiple streamers do not have a notable difference. Streamers that do not lead to substorm auroral onset result in a formation or intensification of such a thin arc, which stays quiet until arrival of the following streamer that leads to onset along the same thin arc.

[25] This sequence is summarized in a schematic illustration in Figure 8. A PBI is formed when no active auroral forms or thin arc exists near the equatorward boundary (Figure 8a), and is followed by an auroral streamer moving equatorward (Figure 8b). The ionospheric manifestation of the associated flow burst, which would be located to the east of the auroral streamer, is also illustrated. This streamer does not lead to auroral onset but leads to a pre-onset thin arc elongated in the east-west direction. This arc stays typically for a few to tens of minutes (~20 min on average) until the onset time or disappears if streamer activity ceases. If another PBI occurs (Figure 8c, typically ~5.5 min before onset [*Nishimura et al.*, 2010a]), and leads to a streamer toward the thin arc (Figure 8d) when the thin arc is present, a substorm auroral onset initiates on the pre-existing thin arc followed by poleward expansion. Based on a statistical analysis using a large number of events obtained during 2007 and 2009, the pre-onset sequence described above is suggested to commonly occur for auroral substorms. Note that the auroral streamer illustrated here is separated from the onset arc by a latitudinally narrow gap, as occasionally seen in observations (e.g., Figure 2f), which corresponds to the enhanced flow channel drawn in blue.

[26] Small intensification of the growth phase thin arc following auroral streamers suggests that each streamer contributes to enhance the plasma pressure gradient in the near-Earth plasma sheet and thus electron precipitation into the upper atmosphere, forming a thin arc. A brighter thin arc during an onset-related streamer suggests that the near-Earth plasma pressure gradient is larger, which may be

more suitable for substorm onset instability to occur, while the pressure gradient would be smaller and the thin arc dimmer or absent during streamers that do not lead to onset. As shown in Figures 2 and 3, the thin arc tends to extend over a wide MLT range near midnight, suggesting existence of an azimuthally extended enhanced plasma pressure gradient region and an upward FAC sheet connecting to it. The difference between streamer sequences suggests that, in addition to precursor flow bursts, existence of a thin arc near the equatorward boundary, which may correspond to a large plasma pressure gradient in the near-Earth plasma sheet created by previous meso-scale flow bursts, may be essential for substorm auroral onset.

[27] We note that the auroral observations we have used do not permit a determination, solely from the observed intensity of a pre-onset thin arc, of whether pressure gradients are sufficiently large for an ensuing streamer to lead to an auroral onset. Nevertheless, the inference that an enhanced pressure gradient may be essential for onset is supported by multispacecraft observations in the plasma sheet that have shown an enhanced duskward pressure gradient forming just prior to substorm onset concurrently with a pre-onset thin arc near the magnetic footprint of the spacecraft [*Xing et al.*, 2011]. The enhanced plasma pressure gradient would give a more favorable condition for some of the previously suggested instabilities, such as ballooning, cross-field current, and Kelvin-Helmholtz instabilities [*Pu et al.*, 1999; *Lui*, 2004, and references therein], although the auroral observations in the present study cannot specify the type of instabilities.

[28] We have identified another important, though less common, sequence. Although the onset is again associated with a streamer propagating toward a pre-onset thin arc, the pre-onset thin arc emerges from diffuse aurora background without a preceding streamer, in contrast to the arc formation associated with a previous streamer. The thin arc tends to form soon after southward turning of the IMF, suggesting that its formation may be related with enhancement of large-scale convection. Therefore, both large-scale and meso-scale convection enhancements could contribute to the thin growth phase arc formation.

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