Reply to comment by Harald U. Frey on "Substorm triggering by new plasma intrusion: THEMIS all-sky imager observations"

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1. Introduction

[1] The sequence of events leading to substorm onset has been a long outstanding issue in magnetosphere-ionosphere coupling physics. *Nishimura et al.* [2010a, hereafter N2010] proposed a potential resolution to this problem based on observations from the all-sky imager (ASI) array [*Mende et al.*, 2008] of the THEMIS project [*Angelopoulos*, 2008], which provides high spatial and temporal resolution auroral images with broad latitudinal and longitudinal coverage. Using the capability of the imager array, we found a repetitive precursor auroral sequence prior to substorm auroral onset. The preonset auroral sequence reported by N2010 is initiated by a poleward boundary intensification (PBI), which is followed by an approximately north-south (N-S) oriented arc (also referred to as an auroral streamer) moving equatorward toward the onset latitude and sometimes turning into an east-west (E-W) oriented luminosity enhancement propagating azimuthally. It finally leads to onset instability in the near-Earth plasma sheet and is observed as auroral onset. Because of the linkage of fast magnetotail flows to PBIs and to N-S auroras, this sequence gives strong support to the idea that onset instability develops following enhanced plasma flows from the open-closed boundary toward the near-Earth plasma sheet [*Lyons et al.*, 2010a, 2010b].

[2] *Frey* [2010, hereafter F2010] has commented on our study of the auroral sequence leading to substorm onset. The main issues raised by F2010 are as follows.

[3] 1. Time differences of auroral intensifications less than 30 min are too short to be called two separated onsets. Thus some of the events considered by N2010 are not onsets but are just intensifications of earlier substorms, and inclusion of such intensifications might affect our statistical results.

[4] 2. A large number of substorms were missed in the N2010 analysis, based on a comparison to the event list by F2010.

[5] In this reply, we first show that the events separated by short time intervals are indeed auroral onsets and that the preonset sequence found by N2010 is commonly seen in both first and subsequent onsets occurring within ~30 min. Then we show that over half of the events in the F2010 list not included in the N2010 study are not substorms but other types of auroral phenomena, and that the majority of the remainder had onsets that were not within the field of views (FOVs) of available imagers. We further demonstrate that the N2010 event list covers most of the F2010 substorm onsets. Finally, we show statistical results using only isolated events and provide evidence that the preonset sequence found by N2010 is common for isolated substorms, and has essentially the same high occurrence probability as for all events.

2. Time Difference Between Onsets

[6] The purpose of the N2010 study was to determine the sequence of events leading to substorm onset for substorm auroral onset events regardless of preceding geomagnetic activity. Thus, we included not only isolated but multiple onset substorms. Each auroral intensification and expansion during such a sequence of substorm expansions has been called the onset of auroral expansion [*Wiens and Rostoker*, 1975; *McPherron*, 1979]. An onset in both types of substorms is commonly characterized by substantial intensification of an auroral arc located near the equatorward boundary of the auroral oval together with an enhancement of westward auroral electrojet. Thus, although F2010 claimed that onsets following the first onset after a short time interval are just intensifications, they can also be separate onsets if they show the typical substorm auroral intensification and are followed by poleward expansion and auroral electrojet enhancements. Using the definition that full breakup events are associated with poleward expansion lasting for more than 3 min [*Akasofu*, 1964], while the shorter breakup events are called pseudobreakup, N2010 selected both types of events that were detected within any of the available imager FOVs. Although we required wide FOVs for the further analysis in Figures 6d–6f of N2010, the event list and Figures 6a–6c (N2010) were produced using onsets that initiated within at least one imager

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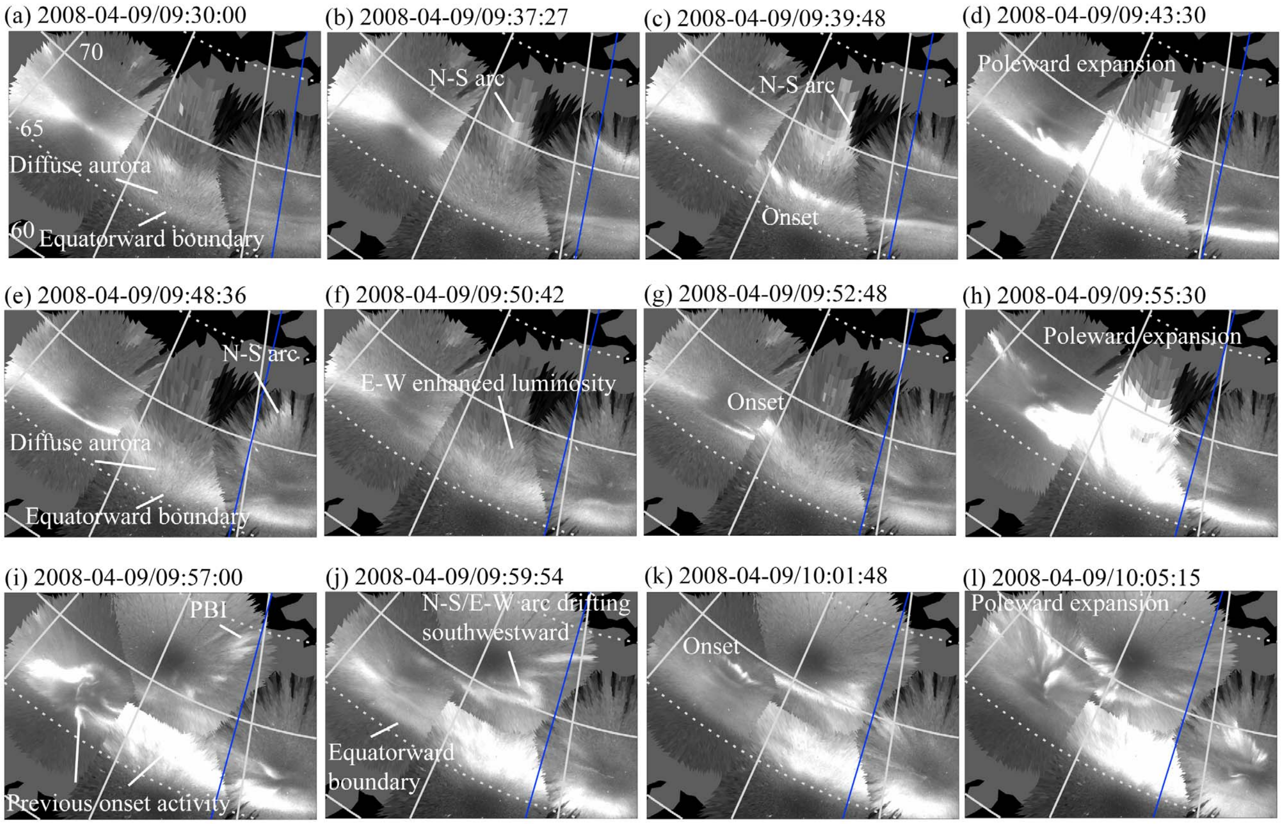

Figure 1. Snapshots of THEMIS ASIs during the three onsets on 9 April 2008. Imagers shown are FSIM, WHIT, and FYKN from east to west. INUV was also available for the last onset. The event sequences of the (a–d) first, (e–h) second, and (i–l) third onsets are shown. White lines are isocontours of magnetic latitude (every 10° in solid lines) and longitude (every 15°). The blue line is the magnetic midnight meridian. The corresponding keograms and magnetograms are given in Figure S1c, and the whole sequence is shown in Movie S1.

FOV regardless of the availability of observations from surrounding imagers.

[7] F2010 detailed 6 days of events and commented that many of the N2010 onsets are closely separated in time and that some events are not onsets followed by poleward expansion but pseudobreakups or just intensifications. We plotted keograms and magnetograms of those events (available in Figure S1) and confirmed that those events showed poleward expansion for more than 3 min, satisfying the definition by *Akasofu* [1964], and intensification of auroral electrojet as can be inferred from negative bays measured nearby the onset locations.[1] These events indeed show new and substantial auroral intensifications after the preceding breakup arcs almost disappeared or significantly weakened, and were often at a different local time than the preceding breakup arcs. Thus, these events are separated from previous breakups and have the same characteristics as onset of isolated substorms.

[8] We agree with F2010's comment that onsets closely separated in time (30 min in work by F2010, though this should depend on the duration of preceding breakup activity) may not be considered as isolated events. However, as mentioned above, N2010 did not intend to focus only on the preonset sequence of isolated substorms but on both isolated and multiple onset substorms. Although auroral intensifications closely spaced in time could occasionally be propagation of previous onset aurora into an observed area, we carefully made sure that the selected events of N2010 are new intensifications separated from poleward expanding aurora from preceding onsets.

[9] We also investigated if there was any discernible difference in the preonset sequences between the first and the subsequent onsets for those events selected by F2010. We show in Figure 1 the auroral sequence of the three onset events closely spaced in time, which occurred at 0939, 0952 and 1001 UT on 9 April 2008. The whole sequence is shown in Movie S1. Poleward expansions and magnetic bays were observed for all three events (Figure S1c), indicating that all of the events are auroral onset events. The onsets were detected within available FOVs, although the FOVs did not cover the poleward boundary of the auroral oval for the first two events. It was both optically and magnetically quiet prior to the first onset, and a quiet diffuse auroral arc was located near the equatorward boundary of the auroral oval (Figure 1a). An N-S arc appeared near the central meridian of the WHIT imager FOV poleward of the diffuse aurora (Figure 1b) and propagated equatorward.

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/ja/2010ja016182. Other auxiliary material files are in the HTML.

Table 1. Classifications of F2010 Events Where Three or More Imagers Were Available During 1 December 2007 and 2 April 2008 (127 Events)[a]

	Onset Within Any Available FOVs	Onset Out of Available FOVs and Propagated In	Other Auroral Features
Number of events	27	30	70
Probability (%)	21.26	25.20	53.54

[a]The third category includes PBIs, north-south arcs, east-west arcs, Harang aurora, pulsating aurora, torch and omega band.

The first onset occurred near the N-S arc meridian and near the poleward edge of the preexisting diffuse aurora (Figure 1c), and then expanded poleward (Figure 1d). The second N-S arc formed in the FSIM imager FOV when the first substorm activity almost ceased (Figure 1e). The N-S arc propagated southwestward and turned into an E-W aligned enhanced luminosity and moved westward (Figure 1f; motion is clearer in Movie S1). The onset occurred near the boundary of the FYKN and WHIT imager FOVs and then expanded poleward (Figures 1g and 1h). A PBI occurred in the INUV imager FOV when the second onset activity still existed (Figure 1i). An N-S arc originated from the PBI and propagated southwestward, forming an approximately E-W oriented arc (Figure 1j). The third onset occurred when this E-W arc moved equatorward and azimuthally and reached the equatorward diffuse aurora (Figure 1k), and then the onset arc expanded poleward (Figure 1l). The preceding active auroral forms almost disappeared by the time of the third onset and did not contaminate the third onset.

[10] The preonset sequence of all the closer together events selected by F2010 can be summarized as follows: It starts with a PBI (if FOVs cover the poleward boundary) and an N-S arc propagates equatorward toward preexisting diffuse aurora located near the equatorward boundary of the auroral oval. The N-S arc frequently turns into an E-W oriented enhanced luminosity and continues propagating westward. Finally auroral onset occurs typically near the poleward edge of preexisting diffuse aurora and the breakup arc expands poleward. This preonset sequence was commonly observed for both the first and following auroral onsets. The sequence of two onsets of the 29 February 2008 event shown by N2010 is also essentially the same. These results indicate that the preonset sequence found by N2010 occurs both for the first and subsequent onsets, as well as for isolated events.

3. Statistical Analysis

[11] F2010 also commented that a large number of substorms were missed in the N2010 list when compared to the F2010 event list, and that there should be more events where three or more ground stations operated under clear sky conditions. To find why the two lists have different numbers of events even in the same period, we surveyed the F2010 event list where three or more imagers were available during 1 December 2007 and 2 April 2008 (127 events; list kindly given to us by H. Frey). We examined the auroral sequences of those events and sorted into three categories: onset occurring within any of available FOVs, onset occurring out of and then propagating into any of available FOVs, and other auroral features (PBI, N-S arc, E-W arc, Harang aurora, pulsating aurora, auroral torch, and omega band). The detailed list is provided in Data Set S1 and summarized in Table 1. We found that only 27 events (21.26%) are substorm onsets initiated within available FOVs. There are 30 more substorms (25.20%) that were detected but these initiated out of available FOVs and then propagated into the FOVs. We found that the rest of the events (53.54%) are not substorm onsets but other types of auroral forms.

[12] Two typical cases of such nonsubstorm events in the F2010 list are shown in Figure 2. Figures 2a–2d show the

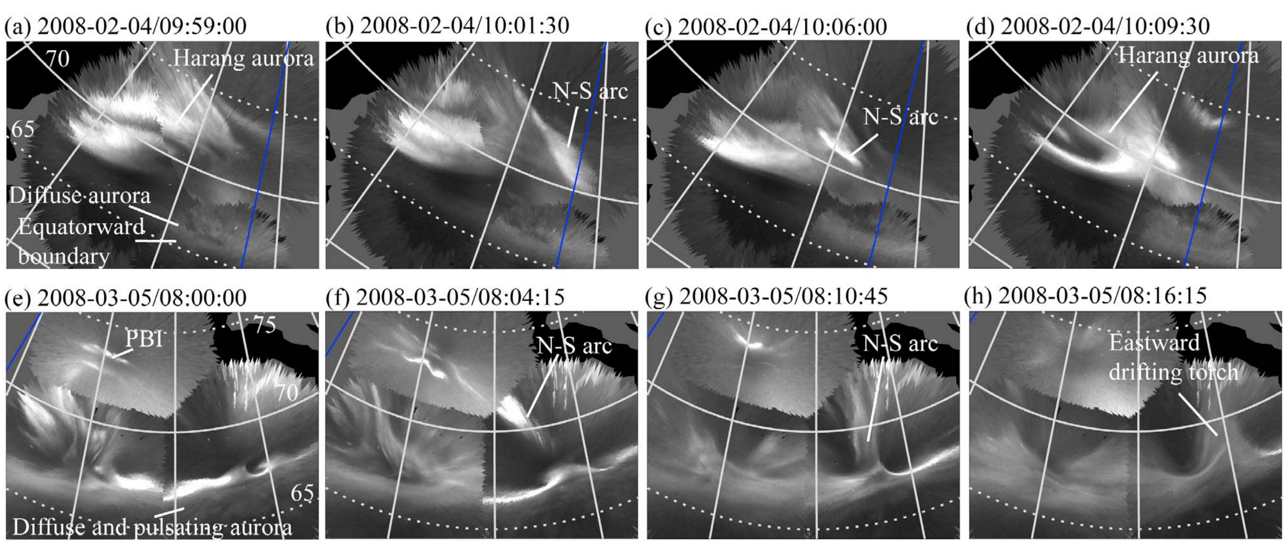

Figure 2. (a–d) Snapshots of THEMIS ASIs during the nononset events in the F2010 list at ~1000 UT on 4 February 2008. Imagers shown are WHIT, INUV, and FYKN from east to west. The whole sequence is shown in Movie S2. (e–h) The 5 March 2008 event using SNKQ, RANK, and GILL imagers. The whole sequence is available in Movie S3.

Table 2. Classifications of the First Category in Table 1 (27 Substorms)[a]

	Both F2010 and N2010	F2010 Only	Unfavorable Observing Condition
Number of events	13	3	11
Probability (%)	10.24	2.36	8.66

[a]The probabilities are the fractions of total events. The third category indicates that the stations that detected auroral onset were partly cloudy or under severe light contamination and thus were not used in the N2010 study.

event occurring at 1000 UT on 4 February 2008. A clockwise streaming auroral feature in the premidnight sector (Harang aurora) persisted throughout this time period. An N-S arc formed near the eastern edge of the Harang aurora and propagated southeastward around the Harang aurora (Figure 2b). This N-S arc appeared at ~1000 UT and can be considered as the auroral signature marked in the F2010 list. However, this arc turned into E-W auroral forms and disappeared without leading to a substorm onset (Figures 2c and 2d). Another N-S arc formed and followed a similar propagation path (Figure 2c) and also disappeared without leading to onset. This type of sequence with N-S and E-W aurora without leading to onset is frequently seen and is believed to be the ionospheric signature of flow bursts within the plasma sheet, which are observed even during nonsubstorm times [*Nakamura et al.*, 2001; *Sergeev et al.*, 2000; *Henderson et al.*, 2002; *Xing et al.*, 2010; *Nishimura et al.*, 2010b].

[13] Figures 2e–2h show the event occurring at 0809 UT on 5 March 2008. A PBI occurred at ~0800 UT (Figure 2e) and propagated southeastward as an N-S arc (Figure 2f). The N-S arc contacted the preexisting arc near the equatorward boundary (Figure 2g) and the whole structure propagated eastward as an auroral torch (Figure 2h). The N-S arc contact at ~0809 UT could be marked as the event in the F2010 list. However, a substorm onset did not occur during this time period. This auroral sequence with an N-S arc forming a torch without substorm onset is also seen frequently especially in the postmidnight sector [*Henderson et al.*, 2002].

[14] Table 2 compares the 27 substorm onsets detected in any of available FOVs (the first category in Table 1) to the onsets included by N2010. Eleven events were not investigated by N2010 because of unfavorable sky conditions for identification of preonset auroral features due to light contamination or partly cloudy skies. Most of the rest of the events (13 events) are included in both the F2010 and N2010 lists, and only three events were missed in the N2010 list. Therefore, we can conclude that both the F2010 and N2010 lists commonly include the majority of the substorm onsets that occurred within any of the available imager FOVs and when the sky condition was favorable for determining the presence of preonset auroral features. As shown in Table 1, many of the F2010 events are not substorms or are onsets that were not covered by available FOVs, and thus N2010 did not investigate those events. The consequence of this is that the F2010 list should not be considered as a list of solely substorm onsets. We believe that this is consistent with what is stated about the F2010 list on the Web page: "There is no guarantee that a certain feature is really a substorm. Some may be better described as pseudobreakups or arc intensification". One thus has to be careful when comparing the F2010 list to the N2010 list because the two lists do not correspond to the same phenomenon. We appreciate that the F2010 list helped us to notice three events missed in the N2010 study.

[15] It is worth showing the occurrence probability of the N2010 N-S arc related preonset sequence only using isolated substorms. We thus removed onset events that occurred within 30 min of a previous onset and or had active auroral forms originated from even earlier substorm activity. The list of N2010 onsets showing which are isolated and which are not, based on the above criteria, is provided as Data Set S2. Figure 3a shows occurrence probabilities of each preonset sequence for 128 events of such isolated events occurring between November 2007 and April 2008. Those events were further divided into poleward expansion and pseudobreakup events (Figures 3b and 3c). Comparing with Figures 6a–6c of N2010 shows that occurrence

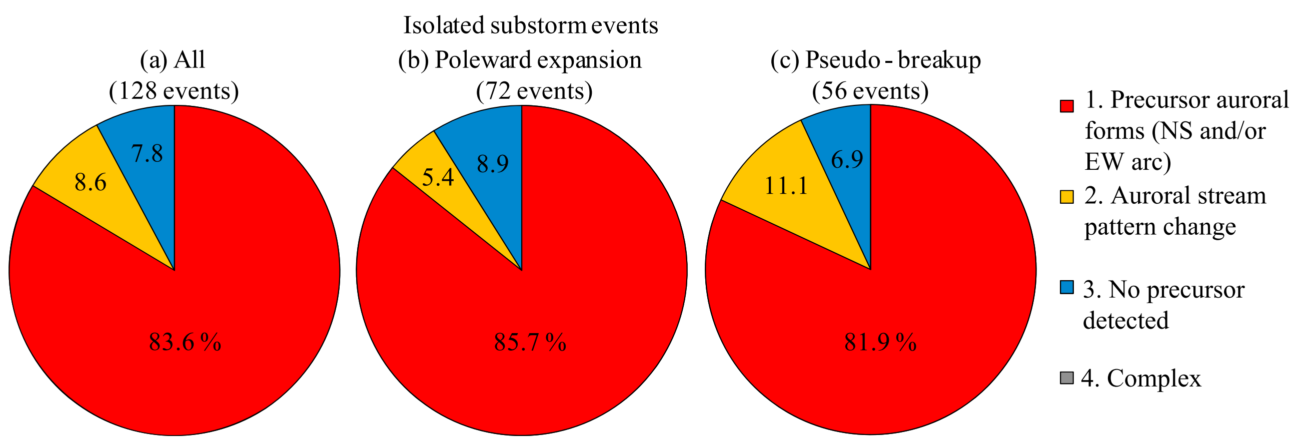

Figure 3. Occurrence rates of preonset auroral forms during isolated auroral intensifications: (a) all events, (b) events with poleward expansion, and (c) events without poleward expansion (pseudobreakup). The definition of categorization is the same as that of N2010. The format is the same as Figures 6a–6c of N2010.

probabilities of each category are essentially the same as those of all onset events including multiple onset substorms: Most of the onsets (83.6% in Figure 3a) are preceded by N-S arcs and/or E-W enhanced auroral luminosity propagating toward auroral onset location. Furthermore, occurrence probabilities of each category for poleward expansion and pseudobreakup events have approximately the same percentages, suggesting that the preonset auroral sequence that N2010 found is common independent of the degree of poleward expansion. Those results lead us to conclude that the preonset auroral sequence found by N2010 is common for isolated and multiple onset substorms.

4. Conclusion

[16] In response to the comments by F2010, we showed using the 6 days of events selected by F2010 that the auroral intensifications occurring a short time after a preceding onset also have onset characteristics, and that all of the events are associated with substantial intensifications of auroral arcs located near the equatorward auroral boundary together with auroral electrojet enhancements. We investigated the preonset auroral sequence for those events and found that the sequence starts with a PBI followed by an N-S arc frequently turning into an E-W arc toward onset location, for both the first and following onsets. Thus, although N2010 included many events of multiple onset substorms, the preonset auroral sequence found by N2010 is common for all events during multiple onset periods.

[17] We further presented statistics showing that such the preonset sequence is frequently identified for isolated substorms and with a similar occurrence probability as found by N2010, who did not separate isolated and multiple onsets. This result indicates that the high occurrence probability of the preonset auroral sequence is common for both isolated and close together onsets. By investigating the events in the F2010 list, we also found that many events in the F2010 list are not substorms but are instead other auroral features such as PBIs, N-S arcs, E-W arcs and auroral torches.

[18] We agree with F2010 that close together onsets are not considered as one isolated substorm sequence. We do not want to debate here whether close together onsets should be considered as one substorm with multiple onsets or multiple substorms. However, our analysis indicates that the preonset auroral sequence is the same for each onset and thus the physical processes leading to each onset is likely the same. We do agree with the final remark by F2010 that the science community should propose a more quantitative definition of substorms based on recent advances in the substorm physics and phenomenology.

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