The azimuthal evolution of the substorm expansive phase onset aurora

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Abstract: We use data from two white light All-Sky Imagers, deployed as part of the THEMIS Ground-Based Observatory program, to explore the azimuthal evolution of the breakup aurora during a pseudobreakup that occurred on November 28, 2005. We find that this breakup occurred on a pre-existing auroral arc. It began with a brightening that formed on an extended region along the arc, and consisted of eastward propagating beads with a wavelength of $\sim$100 km. During the five minutes following the breakup, a second pre-existing arc that was poleward of the first remained undisturbed. The initial azimuthally extended region of enhanced brightness along the arc did not expand further for at least two minutes, after which it expanded rapidly along the arc. From these observations, we conclude that the breakup in this event corresponds to Current Disruption in the inner magnetosphere caused by an instability that creates azimuthally propagating waves and that is not triggered by a fast Earthward flow.

1. Introduction

Identifying the macroscale instability responsible for substorm expansive phase onset is an important goal in space physics. Bringing closure to this question has been the motivation for numerous, theoretical, simulation, and observational event and statistical studies over the years. We now understand that both reconnection in the mid-tail and current disruption in the inner magnetosphere occur as integral parts of the substorm, but their interrelationship and in particular whether one starts and then sets in motion a sequence of events that leads to the other is not currently understood [2, 7, 8]. Careful examination of coordinated *in situ* and ground observations have provided perhaps the best insights in this direction (see e.g., [13, 9]), however it has become clear that although the expansive phase onset unfolds very rapidly, the data with which we are able to address these questions is fundamentally limited in its spatio-temporal coverage and resolution.

In general, substorm event studies are predicated on the idea that the correct combination of solar wind, *in situ*, and remote sensing of the ionospheric electrodynamics from the ground and space would be able to provide sufficient information to rule out some proposed onset mechanisms and provide constraints for models and simulations used to explore mechanisms that are still viable. For example, the typical substorm *breakup arc* is embedded in the bright proton aurora which maps to the transition between tail-like and dipolar field lines [12, 3, 4], most often in the region between geosynchronous orbit and L$\simeq$10Re. We also understand that the breakup, substorm current wedge, current disruption, dipolarization, and injection are all manifestations of the same inner Central Plasma Sheet (CPS) disturbance (see, for example, [9]). The ground-based auroral and magnetic field data in particular point to a disturbance that begins in the inner CPS and evolves azimuthally and meridionally, the latter reflecting radial evolution in the magnetosphere [5], consistent with the Current Disruption (CD) paradigm. However, attempts to create a synoptic picture of the evolution of the expansive phase from analysis of combined *in situ* and ionospheric remote sensing data has led to a more ambiguous picture, leading to at least three sets of inconsistent conclusions: 1) expansive phase began in the inner CPS after which it progressed tailward (consistent with the CD paradigm); 2) expansive phase began in the mid-tail with reconnection, fast Earthward flows, and subsequent inner CPS effects (i.e., consistent with the Near-Earth Neutral Line or "NENL" paradigm); 3) that the mid-tail and inner CPS expansive phase processes might evolve largely independently of one another [9, 11, 13, 10, 17].

Bringing closure the question of how and where expansive phase onset is initiated in the magnetotail is the primary scientific motivation for the upcoming NASA Time History of Events and Macroscale Interactions in Substorms (THEMIS) MIDEX mission. THEMIS represents the first true constellation-class geospace mission, and will involve five satellites on equatorial orbits. The orbits will have 1, 2 and 4 day periods, corresponding to $\sim$10, 20, and 30 Re apogee distances, respectively. The outer two satellites will be at or near apogee for more than ten hours every four days. The inner three will together provide coverage of the $\sim$10 Re region for those same ten hours. Throughout the mission, the apogee conjunctions will be over central Canada, on a meridional line bracketed by GOES East and West. During the winter months, apogee will be in the magnetotail, where the seven THEMIS and GOES satellites will bracket the NENL and CD regions. Although the THEMIS constellation will provide numerous and unprecedented opportunities to study the radial evolution of the expansive phase in the magnetotail, the satellites by themselves would not be able to bring closure to the question at hand. While it is true that the expansive phase evolution is most often couched in radial terms (as outlined in the previous two paragraphs), the disturbance also evolves azimuthally. Thus, although data from the satellites might indicate a clear ordering of events, it might also be that the process started away from the apogee

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meridian and later swept over it.

The THEMIS program has a ground-based component which is specifically designed to deal with the azimuthal uncertainties that would be present if all that was available were satellites on a more or less radial line through the CPS. The apogee meridian was chosen to be over central Canada to take advantage of the fact that a large fraction of the auroral oval is over land in northern Canada and that ground-based space science instrumentation is already operating in that sector (e.g., instruments operated by Canadian GeoSpace Monitoring, SuperDARN, the University of Alaska Geophysics Institute, MACCS, and other programs). In addition, a continent-wide array of fluxgate magnetometers and white light auroral imagers is being deployed specifically as part of THEMIS. In Figure 1, we show the locations and fields of view (FOVs) of the 20 All-Sky Imagers (ASIs) that make up the THEMIS ASI array.

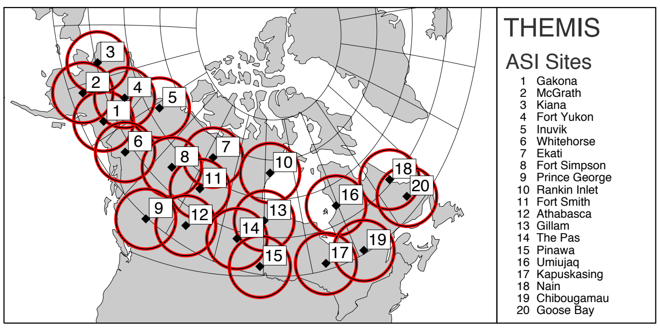

Fig. 1. Fields of view of white light ASIs that will be operating as part of the THEMIS Ground-Based Observatory network. The fields of view assume 110 km emissions 10 degrees above the horizon. The black contours indicate constant magnetic latitude and longitude (Altitude Adjusted Corrected Geomagnetic Coordinates or "AACGM" Epoch 2000 - [1]). The magnetic latitude contours are for 60° through 80° in 5° increments. The magnetic longitude contours are separated by one hour of magnetic local time.

The THEMIS ASIs will take one image every three seconds. Imaging will be synchronized across the array with Global Positioning System (GPS) timing. While the ASIs and magnetometers will provide essential contextual information in support of THEMIS meeting its objectives, these new instruments will also bring something truly new to substorm studies. For example, existing arrays of ground-based optical instruments have provided numerous instances of simultaneous observations across all relevant latitudes. The Finnish MIRACLE ASI, Canadian NORSTAR ASI, and CANOPUS Meridian Scanning Photometer arrays are but three examples of this (see e.g., [5]). The azimuthal evolution of the expansive phase aurora has been extensively studied using global auroral imagers on satellites, but the temporal and spatial resolution afforded by those instruments have not been sufficient to explore the details of the expansive phase onset (see e.g., [6]). Since we know that, at the time of the auroral breakup, the auroral features can evolve azimuthally (i.e., east-west) beyond the FOV of a single imager (see [16]) in several tens of seconds, being able to track the evolution of the expansive phase aurora across several hours Magnetic Local Time (MLT) with three second temporal resolution will be an important step forward in constraining substorm theories.

One of the great advantages to being involved in the ground-based component of a mission like THEMIS is that we have data before the satellites are launched. Deployment and operation of the imagers started in 2004, and the array will be completely in place by the fall of 2006. By the end of the northern hemisphere 2005-2006 winter, there were 13 ASIs operating in Canada and Alaska. Summary keograms and thumbnail images can be seen on the "GAIA" auroral virtual observatory (http://gaia-vxo.org).

In this paper, we present data from a small substorm that occurred over the Alaska-Canada border region. The initial auroral breakup was in the FOV of one ASI and quickly spread east into that of an adjacent imager. We have two objectives in this paper. First, we want to highlight some of the new capabilities that the THEMIS ASI array will bring to the THEMIS program and substorm studies in general. Second, we want to explore the azimuthal evolution of the breakup aurora on a time scale of tens of seconds, and comment on what the auroral data indicates in terms of the substorm onset mechanism. We point out in advance that we are presenting data from only one event. Further, as the auroral expansion lasts only $\sim$10 minutes, and as it does not appear to lead to lobe flux reconnection, this event is a pseudobreakup (see [17] and references therein for what we mean by "pseudobreakup").

2. The Event

The event that we focus on occurred between 10:00 and 10:30 UT on November 28, 2005. In the several hours leading up to the event, the solar wind speed and dynamic pressure were relatively steady, and consistently below 400 km/s and 4 nPa, respectively. As well, during the time leading up to the event the Interplanetary Magnetic Field was consistently southward. In short, the IMF and solar wind plasma observations do not indicate any trigger for the event. At $\sim$10:10 UT, a $\sim$ 200 nT negative H-bay was observed in western Canada and Alaska (see below). The event does not have any noticeable signature in the geosynchronous GOES East or GOES West magnetic field data. In Figure 2, we show FUV auroral images from the IMAGE WIC instrument for this event. The auroral breakup is evident in the 23:00-24:00 MLT sector, starting first at roughly $\sim$10:14 UT, and ending by $\sim$10:20 UT.

On that night, there were relatively clear skies over two of the THEMIS ASIs under the region where the auroral breakup shown in Figure 2 occurred. These were the Fort Yukon (Alaska, USA) and Whitehorse (Yukon, Canada) ASIs, the FOVs of which are shown in the expanded map in Figure 3. In Figure 4, we show a sequence of auroral images at 12 second intervals (top) from the Fort Yukon ASI, and the X-component magnetic field data from the Fort Yukon magnetometer (bottom). Looking first at the ASI images, we see the onset arc was in the south of the imager FOV, located at roughly 64° magnetic latitude (see Figure 3). The image sequence begins at 10:12 UT, at which time the substorm brightening was already visible in the south. As well, there was a quasi-stable auroral arc just slightly north of overhead in the imager. Over the next $\sim$5 minutes, the brightening evolved into a vortex which grew poleward and azimuthally. It was only after $\sim$10:17 UT (i.e., more than 5

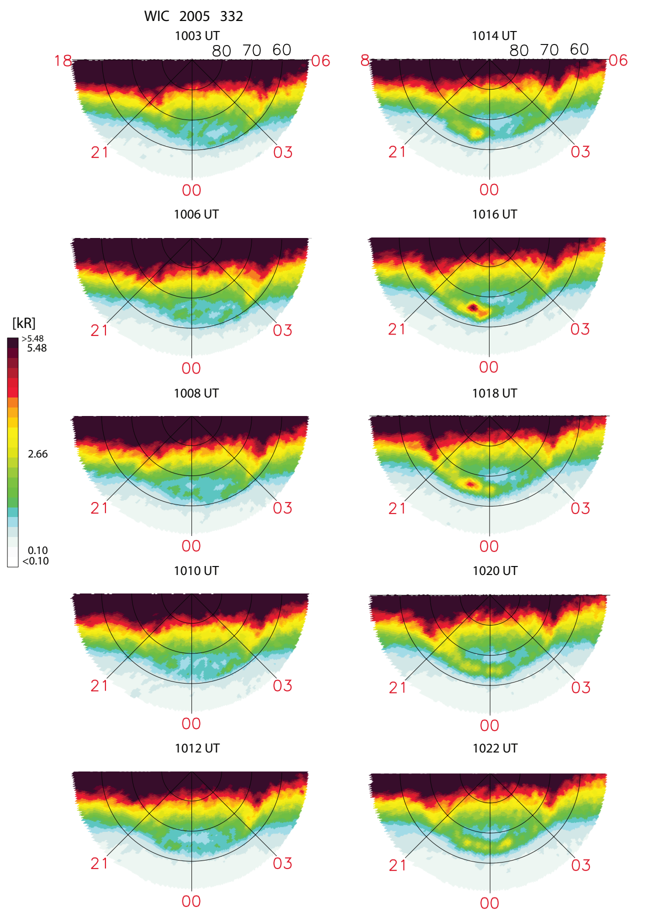

Fig. 2. IMAGE WIC FUV auroral images obtained in the southern hemisphere have been mapped into geomagnetic coordinates and subsequently into the northern hemisphere to produce this figure.

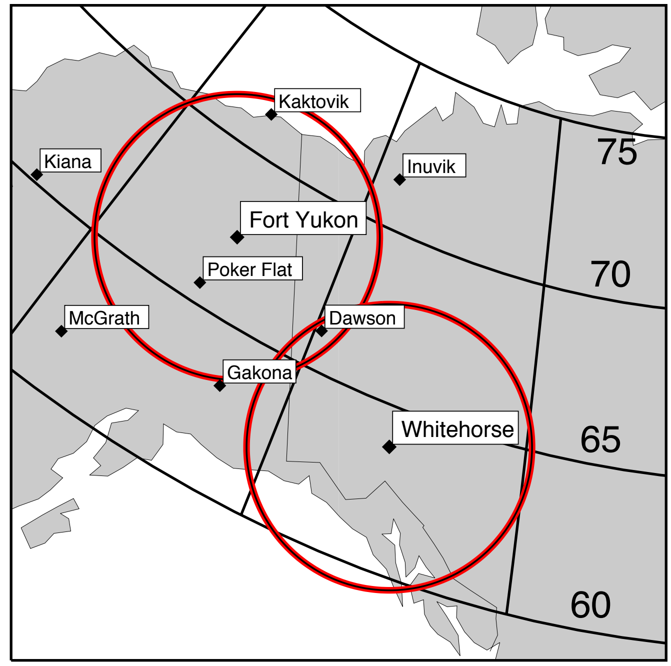

Fig. 3. Fields of view of the two THEMIS ASIs that obtained the white light images used in this study. These two imagers are located at Fort Yukon in Alaska and Whitehorse in Yukon Canada. The black contours indicate constant magnetic latitude and longitude (AACGM Epoch 2000). The magnetic latitude contours correspond to 60° through 75° in 5° increments. The magnetic longitude contours are separated by one hour of magnetic local time.

minutes after the initial brightening) that the more poleward arc was noticeably disturbed. The image sequence spans the time period bracketed by the two dashed lines in the lower panel, and hence the time during which there is an enhanced westward electroject and corresponding negative H-bay.

In Figure 5, we focus in on the step-by-step development of the auroral breakup from 10:11:12 until 10:12:54 UT. As the arc that brightened was in the southern part of the FOV of the Fort Yukon ASI, we restrict our attention to partial images, which comprise the left-hand column of the figure. The image at 10:11:12 UT is the first image in which there is unmistakeable evidence of the onset. Note that this is more than a minute before the negative H-Bay is noticeable in the Fort Yukon magnetometer data, and a full three minutes prior to the pseudobreak being clearly evident in the IMAGE WIC data. In the right-hand panel of Figure 5, we show differences between successive images (see figure caption), which highlight the wave disturbance more clearly than do the raw images. The difference image sequence shows a bead-like structure that emerges on the pre-existing breakup arc. Over the nearly two minutes spanned by the image sequence, the beads brightened, and propagated eastward (note that examination of the three second data shows that there is no problem with aliasing). The wavelength and azimuthal propagation speeds of the beads were estimated at ∼100 km, and ∼5 km/s, respectively (presuming 110 km altitude emissions).

Referring to Figure 3, the arc visible to the south of Fort Yukon must have extended into the poleward part of the Whitehorse FOV. In Figure 6, we show a time sequence of partial images from Fort Yukon and Whitehorse side by side. Before 10:12:00 UT, the brightening was restricted to the Fort Yukon FOV, although it did expand rapidly in the azimuthal direction, involving the entire arc within the FOV in less than 30 seconds. By 10:12:24, the brightening was clearly visible on the arc at the western edge of the Whitehorse FOV. For the next 90 seconds, the eastern edge of the disturbance remained fixed. That is, the brightening extended azimuthally along the arc until it appeared just inside the Whitehorse field of view, at which time the azimuthal growth stalled for 90 seconds or more. By 10:14:24, the brightening was spreading rapidly eastward along the pre-existing arc. The speed of this expansion was ∼0.5 km/s.

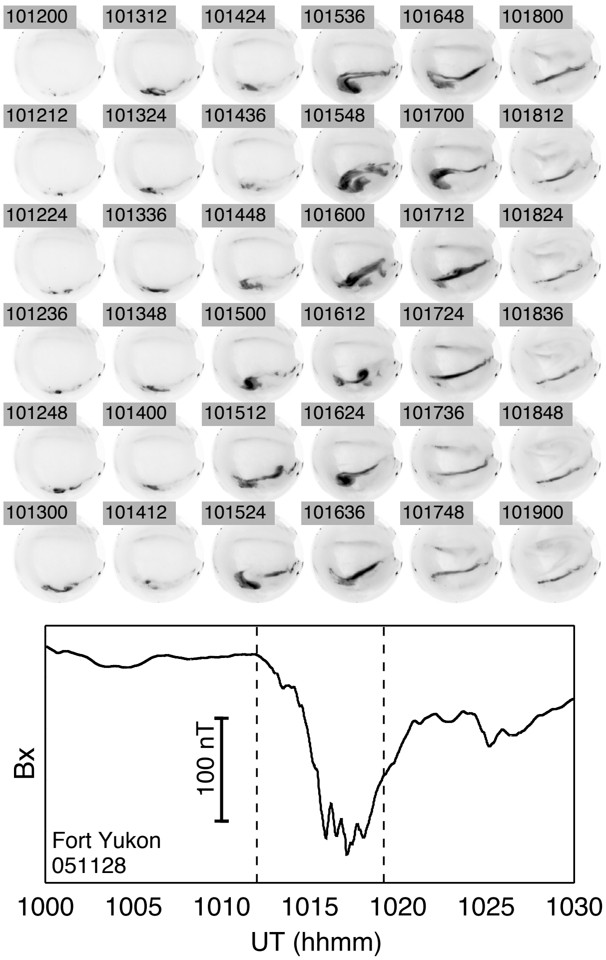

Fig. 4. The negative H-bay associated with the pseudobreakup is clearly evident in the Fort Yukon magnetometer data. Images are from the Fort Yukon THEMIS ASI, separated by 12 seconds, and spanning the time range indicated by the two vertical dashed lines. UT for each image shown is indicated in the grey boxes and is given in hhmmss format.

3. Summary

This event was a pseudobreakup that does not appear to have been triggered by changes in the interplanetary medium. The event unfolded in just over ten minutes. Seen in ASI data, the event began with a brightening that spread rapidly along the pre-existing arc. While this azimuthal expansion was occurring, there was a well-defined wave form in the brightness along the arc that grew in intensity and also propagated rapidly eastward. The azimuthal expansion stalled for 90 seconds or more, and then proceeded further with the brightening extending across the entire FOV of the Whitehorse ASI over the next two minutes. While this expansion phase was unfolding, there was a pre-existing arc poleward of the breakup arc that remained undisturbed until at least five minutes after the initial brightening.

As discussed in the Introduction, there is intense debate over what macroscale instability leads to the expansive phase onset. While the data that we present here in this paper is only for one event, and utilizes data from only two of the soon to be 20 THEMIS white light ASIs, it brings forward some interesting points. First of all, the pre-existing arc that brightened was equatorward of another pre-existing arc. That arc remained undisturbed for at least five minutes while the expansive phase is clearly unfolding. Although we do not have proton auroral data available for this event, the onset arc was at only 64° magnetic latitude, and so in this event was likely embedded in the bright proton aurora (see the relevant discussion in the introduction). Further, the auroral brightening occurred at the same time as the negative H-Bay, and so it is compelling to associate it with CD in the inner CPS. Thus, if the CD was initiated by the braking of a fast flow that was in turn launched by mid-tail reconnection, then all of the dynamics leading up to the CD created no auroral signatures that were detectable by the THEMIS ASIs, and had no detectable effect on the second, poleward arc. Thus, subject to the caveats discussed below, these observations are (in our opinion) more consistent with the CD rather than the NENL model.

The azimuthal propagation of the beads that formed during the first few minutes of the brightening point to the growth of a wave in the CPS magnetically conjugate to the arc. Although this is only one event, the azimuthal structuring and propagation were very clear, and occurred during the first 1.5 minutes of the brightening, and commensurate with the formation of the negative H-bay. It is thus compelling to associate these waves with an instability that leads to a decrease in the cross-tail current. In a recent study, [11] used Cluster observations to show the presence of eastward propagating waves during the initial several minutes of expansive phase onset, and argued that these waves were a manifestation of ballooning mode instability. Those authors went on to argue that the azimuthal structuring would lead to filamentation of the perpendicular current in the current sheet, and via $\nabla \cdot \vec{J} = 0$ would generate periodic and eastward propagating filaments of parallel current. This could account for the bead-like structuring of the breakup arc shown in Figure 5.

The initial brightening occured in the FOV of the Fort Yukon ASI. The brightening rapidly expanded azimuthally until it was in the FOV of the Whitehorse ASI (we have no images from west of Fort Yukon so we do not know how far expansion went beyond the western edge of the FOV of the imager). At that time, the azimuthal expansion stalled, only to pick up again several minutes later. Our interpretation of this is that the instability that gave rise to the eastward propagating structures discussed in the previous paragraph formed virtually instantaneously (i.e., in less than 30 seconds) in an azimuthally extended but radially localized region in the CPS. Again, in our view, this region in which the initial instability formed was magnetically conjugate to the part of the arc that initially brightened. It is interesting to note that a separate study found that the radial and azimuthal extent of the initial dispersionless injection region is azimuthally extended and radially limited in much the same way [15]. Further, that study also found that, on average, the initial dispersionless injection region forms outside of geosynchronous distance, most likely 8-10 Re from the Earth.

These results are obviously preliminary, and are subject to several important caveats. First, we have no idea what an auroral arc corresponds to in the magnetosphere. This is a tremendously troubling issue given our field's reliance on the evolution of discrete aurora in studying the expansive phase onset. Second, in this particular case, we do not have some fundamentally important complementary observations that would allow us to place the two arcs in the Fort Yukon FOV in a better magnetospheric context. On the one hand, if we had good complementary proton auroral observations, then we would be able to place the breakup arc relative to the ionospheric footprint of the transition between dipolar and tail-like field lines (which is where we believe that arc maps to). On the other hand, if we had good 630 nm auroral "redline" observations, we would know where the open-closed boundary was relative to the poleward arc. This latter point would allow us to assess how strongly the lack of disturbance of that arc supports the notion that formation of a NENL and subsequent fast flows cannot have preceded this auroral breakup. Subject to these caveats, we assert that the data presented here supports the following conclusions for this event:

1. the breakup corresponded to CD in the inner CPS.
2. the CD was not triggered by fast Earthward flows.
3. the breakup was initiated by an instability that produced azimuthally propagating waves.
4. the initial instability formed in a radially localized but azimuthally extended region in the CPS.
5. our results are consistent with the CD rather than the NENL substorm model.

As we come into the THEMIS era, it is clear the the THEMIS ASI array will provide synoptic white light images with unprecedented spatial and temporal resolution. Future work along the lines of this study will involve the building up of a repertoire of events, comparing wavelengths and propagation with those predicted for magnetospheric waves and instabilities, and attempts to better constrain the mapping between the magnetosphere and ionosphere. Finally, we point out that we need to develop an understanding of what auroral arcs correspond to in the magnetosphere.

Acknowledgements

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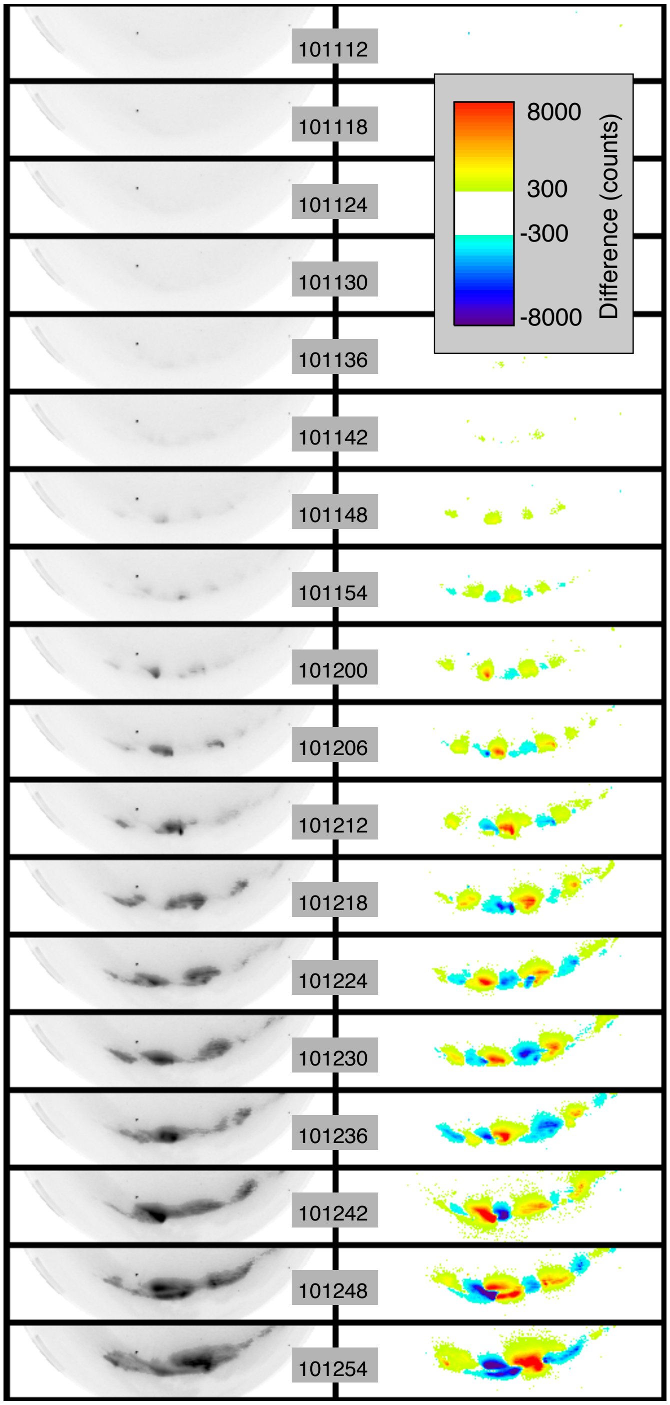

Fig. 5. The left column consists of partial Fort Yukon white light ASI images (roughly the bottom quarter of the image in each case) separated in time by 6 seconds with time increasing down on the plot. The time corresponding to each image is indicated in hhmmss format. The images go from 10:11:12 UT through 10:12:54 UT, and so span 1 minute and 42 seconds (as an aside, we note that the THEMIS ASIs will operate at a cadence of one image every three seconds. The right hand column consists of differences between successive images in false color. We have mapped a range of differences around zero to white so as to suppress the effects of CCD readout noise.

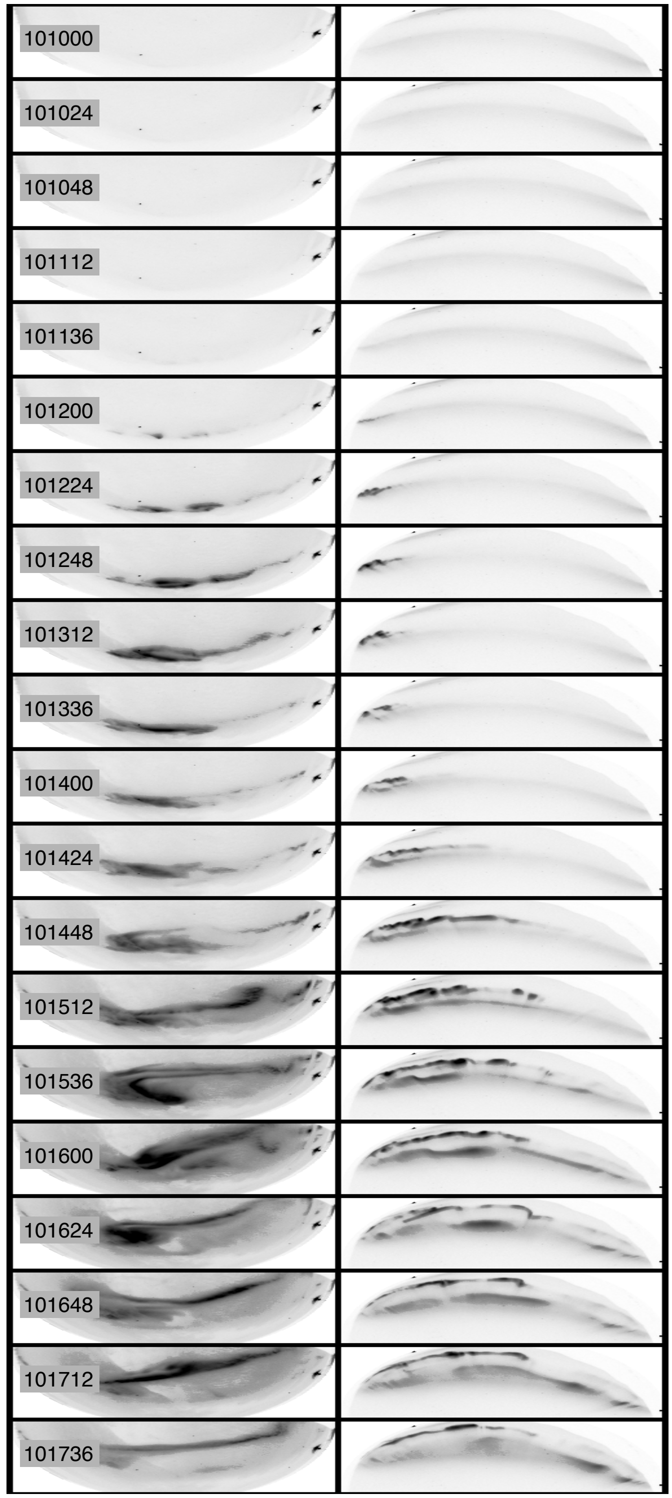

Fig. 6. The onset and subsequent expansion can be seen in the images collected by both the Fort Yukon and Whitehorse imagers (see Figure 3). The onset arc is in the southern part of the Fort Yukon field of view and the northern part of the Whitehorse field of view. In this figure, we show subsequent (time increasing downwards) partial images from the Fort Yukon (left) and Whitehorse (right) ASIs. The Fort Yukon partial images are roughly the bottom third of the field of view. The whitehorse images are roughly the top one third of the field of view.