Observation of an Isolated High-Speed Auroral Streamer and Its Interpretation as Optical Signatures of Alfvenic Fronts Generated by Bursty Bulk Flows

W. W. Liu\textsuperscript{1}, J. Liang\textsuperscript{1}, E. F. Donovan\textsuperscript{2}, T. Trondsen\textsuperscript{2}, G. Sofko\textsuperscript{3}, B. Jackel\textsuperscript{2}, C.-P. Wang\textsuperscript{4}, S. Mende\textsuperscript{5}, H. U. Frey\textsuperscript{5}, and V. Angelopoulos\textsuperscript{5,6}

Abstract. The THEMIS All-Sky Imager at Fort Smith, Canada observed a sudden appearance and subsequent evolution of an auroral streamer on April 15, 2006. The event took place in an oval that was optically dark, and did not lead to a substorm breakup. We characterize the event as an isolated streamer; similar events have been previously linked to bursty bulk flows in the magnetotail. Thanks to the high time and spatial resolution of THEMIS ASI, the observed streamer reveals many detailed features hitherto not observed. Aside from their exceptionally high speed and fine transient structures, the

\textsuperscript{1} Space Science Branch, Canadian Space Agency, St-Hubert, Quebec, Canada
\textsuperscript{2} Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada
\textsuperscript{3} Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, SK, Canada
\textsuperscript{4} Department of Atmospheric and Oceanic Sciences, UCLA, Los Angeles, CA
\textsuperscript{5} Space Science Laboratory, University of California at Berkeley, Berkeley, CA
\textsuperscript{6} Department of Earth and Space Sciences, UCLA, Los Angeles, CA
streamers are found to exhibit an unusual convergent motion (equatorward from high latitudes and poleward from low latitudes) to form a complete flow channel. Our analysis shows that this observation is best explained with a new theory on the origin of auroral streamers.
1. Introduction

Auroral streamers are north-south aligned structures that usually have an apparent equatorward motion in the oval. They have been associated with the Bursty Bulk Flows (BBF) [Henderson et al., 1998; Sergeev et al., 1999; Nakamura et al., 2001; Kauristie et al., 2003; Zesta et al., 2006]. While BBFs have been observed in-situ in the magnetotail under practically all geomagnetic activity conditions [Baumjohann et al., 1990; Angelopoulos et al., 1994] albeit at higher frequency at active times, auroral streamers are predominantly observed in an active oval, particularly during the recovery phase, a period when auroral expansion has reached the polar cap boundary. Recovery-phase auroral streamers can be explained by two mechanisms. In what is often referred to as the Poleward Boundary Intensification (PBI) model, interplanetary conditions or internal magnetospheric processes might trigger midtail reconnection, which in turn produces fast earthward (equatorward) flows [e.g., Lyons et al., 1999]. Alternatively, it has been shown that compressional waves launched by substorm expansion can be absorbed at the density ramp at the plasma sheet boundary layer and resonantly couple to Alfven waves; the resulting field-aligned current distribution has an apparent equatorward motion [Liu et al., 1995].

BBFs have been proposed as a mechanism of transporting energy and flux to the near-Earth magnetosphere [Angelopoulos et al., 1994]. During the growth phase, earthward moving BBFs have been invoked as a potential trigger of substorm onset [e.g., Shiokawa et al., 1998]. Observation of an “isolated” auroral streamer in an oval that is not subject to global substorm expansion can help us monitor the elusive midtail reconnection and
probe its consequences. However, auroral streamers are difficult to detect under an optically quiet oval; the optical signature is by definition weaker, and the event itself might be less frequent. As the observations in this paper will reveal, streamers contain fine structures that are very dynamic, with lifetime less than 10 s. Existing space-borne imaging cannot capture, much less track, these changes. The deployment of the THEMIS ground-based observatory (GBO) white light, All Sky Imager (ASI) array has improved the detection capability, owing to its fast cadence and high sensitivity (see Donovan et al. [2006] and Mende et al. [2007, 2008] for details of the THEMIS GBOs).

In this paper, we report on an auroral streamer event observed by a THEMIS GBO ASI, within an oval that has been optically dark for ~10 min. The preceding quiescence provides confidence that the event was due to local, rather than global processes. In other words, the observed streamers are more likely to have originated from midtail reconnection than global resonant coupling. The reported event reveals some puzzling features that defy the standard explanation and require alternative interpretations. The observations are best reconciled by linking streamers to the propagation of Alfven wave front launched by a BBF. The revised theory predicts a “supra-kinematic” streamer motion with speed faster than the mapped BBF speed in the ionosphere. More dramatically, a very fast BBF can outrun the Alfven waves to the ionosphere and gives the appearance of a poleward moving auroral streamer, as observed in the event under study.

2. THE AURORAL STREAMER EVENT ON 15 APRIL, 2006

On 15 April, 2006, between 07:32:30 and 07:36:00 UT, the THEMIS GBO ASI at Fort
Smith imaged a high-latitude auroral activation and the ensuing development of auroral streamers. The event occurred in the premidnight quadrant, near 23 h MLT. Prior to this interval, the IMF $B_z$ was predominantly southward (a few nT) for roughly 40 minutes (data not shown). WIND and ACE observations indicate a sudden northward turning of the IMF at roughly 07:32 UT (extrapolated time to the nominal bow shock distance). For about 10 minutes prior to 07:32:30, there is a general absence of auroral activity within the ASI’s FOV.

In Figure 1, we present the keogram of the NORSTAR multispectral imager (MSI) co-located with the THEMIS ASI in Forth Smith. The keogram is at 30-s time resolution and covers 07:00 – 08:00 UT. At approximately 07:05 UT, there is a pseudobreakup that fades in about 5 minutes. At 07:18, there is a poleward boundary intensification marked by the green box. The 630 nm green line emission expands both poleward and equatorward afterward for about 7 minutes. After 07:25 UT, there is a lull of activity until another PBI at 07:31:30, marked by the second green box. Again, the poleward boundary exhibits a steady equatorward movement prior to the activation, and a bifurcating motion follows after the brightening. Unlike the previous activation, the second PBI leads to a long-lasting (>20 min) series of equatorward moving streamers. It is important to note, however, despite the apparent strong driving from the poleward boundary, the apparent flow of energy is predominantly equatorward in the 1-h window shown in Figure 1, with the exception of the brief pseudo-breakup at 07:05 UT. Because of the absence of poleward expansion of aurora originating from low latitudes, we believe that the magnetosphere is under the steady magnetospheric convection.

Figure 2 shows the high-resolution picture a small slice of the event (marked with
arrow in Figure 1), as seen by the THEMIS ASI at Fort Smith. Because of the relative quiescence of the oval in the preceding 8 minutes, we characterize the event as an isolated streamer. The circles of different styles mark the beginning and ending of sub-events we would like to highlight. At the start of sub-event 1 at 07:33:48 UT, the high-latitude activation at ~68.5° has been in progress for ~1.5 min. The first evidence of brightening is visible as a speck at magnetic latitude 68.1° and magnetic longitude –54.5° at 07:32:15 UT, which spreads to cover almost 1 h MLT in longitude, but with no visible signs of streamer until 07:33:48 UT. At the beginning of sub-event 1, there is an equatorward striation from the primary activation region, and a detached blob brightening more than 1° equatorward. In the ensuing seconds, the primary activation striation extends equatorward, so does the detached blob, with the two never fully establishing continuous connection at the end of sub-event 1 at 07:34:03. During the 15-second interval of this sub-event, the blob has moved ~0.5° equatorward, giving an average speed of 3.6 km/s. The detached blob begins to disintegrate at 07:34:06, which we mark as the beginning of sub-event 2. The second event is marked by the illumination of a narrow channel (~0.5° magnetic longitude) connecting the primary activation region and the location where the detached blob used to be. What is puzzling about this connection is that auroras from the primary activation region and remnant of the detached blob appear to move against each other. Specifically, features connected to the high-latitude luminosity races equatorward and those connected to the low-latitude luminosity races poleward. Within 2 frames (6 s), the counter-moving streamers have covered a distance about 1°, giving a relative speed of ~18 km/s. Lest that the counter-streaming connection
is a rare occurrence, we look at sub-event 3 immediately following at 07:34:21. The head of the lower-latitude stream is a remnant of a detached blob similar to the one reported in sub-event 1. Again, the equatorward- and the poleward-moving striations make a clear connection. In this instance, the connection is complete in ~9 seconds over ~1°, giving a closing speed of ~12 km/s, and carves out a separate flow channel about ~1° MLT east of the channel formed by sub-event 2. We thus conclude that poleward auroral streamers are not observational oddities.

We have examined the SuperDARN observation over Fort Smith. There is no overlapping beam coverage at the time, but the westernmost beam of the Saskatoon radar skims through the Fort Smith ASI FOV. Between the 07:32UT and 07:34 UT sweeps, the Saskatoon radar line-of-sight speed jumps from 300 m/s to 1,100 m/s. While the jump is consistent with the observation of the streamers, the LOS speed is a far cry from the inferred auroral streamer speed.

Since it is unlikely that two independent structures should merge smoothly into one narrow flow channel, let alone a replay within seconds of each other, we believe that the detached blob is somehow related to the primary activation. This begs the question how they are related and what causes the narrow, counter-streaming auroral forms.

3. THEORETICAL INTERPRETATION

The observations reported in the previous section are not easily explained by the standard theory of auroral streamers. The BBF model proposed by Pontius and Wolf and later refined by Chen and Wolf [1993] postulates that plasma bubbles underpopulated with particles divert perpendicular currents to the ionosphere, which in turn generates a
secondary electric field that drives the bubble to move earthward. The Pontius-Wolf-Chen (PWC) theory implies that auroral streamers reflect the bulk motion of the underpopulated flux tube and should be visible as a flow burst in local convection. However, in the two sub-events considered in the previous section, the inferred streamer speed is larger than the convection speed measured by SuperDARN by an order of magnitude. See Kauristie et al. [2003] for a similar estimate of streaming speed. If we take 100 as the latitudinal mapping factor at ~68° magnetic latitude, an ionospheric speed of 10 km/s corresponds to 1000 km/s in the equatorial plane. Whereas flow bursts in excess of 1000 km/s are occasionally observed in the magnetotail, the majority of such events have peak speeds in the 400-500 km/s range. Therefore, the streamer event of 15 April 2006 is supra-kinematic, in the sense that its speed is higher than the mapped speed of its proposed BBF source. How is it possible that the streamer outruns its magnetospheric progenitor?

In fact the situation is more perplexing. The detached blobs and formation of flow channels by counter-streaming cannot be explained by the PWC, unless one invokes contorted magnetospheric motions not consistent with the theory itself.

The cumulative evidence presented here suggests that auroral streamers do not mirror the bulk motion of flux tubes. When a flux tube experiences a highly dynamic evolution such as a BBF, the ionospheric and magnetospheric motions are partially decoupled, because motions caused by the inductive electric field do not transfer to the ionosphere (e.g., Liang and Liu [2007]). It is thus not surprising that the SuperDARN observations do not come close to the streamer speed. As an alternate theory, we propose that the Alfvén waves generated by magnetospheric processes are the cause of auroral streamers.
Suppose a flow burst with velocity $v$ is launched from point $x_0$ at time $t_0$. As the plasma jets earthward, it perturbs its surrounding, and Alfvén waves are launched from the head of the burst. As the Alfvén wave reaches the ionosphere, its electric field perturbation is reflected to almost exactly cancel that of the incident wave. In contrast, the reflection coefficient of the transverse magnetic field perturbation is $\sim 1$, meaning that the field-aligned currents carried by the incident and reflected waves reinforce each other. For abrupt activations, the resulting $E$ and $B$ perturbation exhibits an oscillatory approach to an equilibrium state, and the frequency of the oscillation is in the 0.1-1 Hz range, according to the Alfvén resonator theory [Lysak, 1999 and references therein]. Accordingly, we expect the head of an auroral stream to be accompanied by strong field-aligned currents (hence auroral luminosity) and relatively slow convection.

For the Alfvén wave front created at time $t_0$, the traveling time to the ionosphere is given by $t_A = \int ds/v_A = \sqrt{\mu_0 \rho} \int ds/B = \sqrt{\mu_0 \rho} V$, where $\rho$ is plasma mass density, $V$ is the unit flux tube volume between the equator and ionosphere. We have assumed that the plasma density is a constant along field lines, consistent with an isotropic distribution function that is usually observed in the CPS. At time $t_0 + \Delta t$, the head of the flow burst is at $x_0 + v_{BBE} \Delta t$. At this point, another Alfvén wave is launched to the ionosphere. The first Alfvén wave will arrive at time $t_0 + \sqrt{\mu_0 \rho} V$ at the ionospheric footprint of the field line threading $x_0$, and the second Alfvén wave will arrive at $t_0 + \Delta t + \sqrt{\mu_0 (\rho + \Delta \rho)} (V + \Delta V)$, at the footprint of the field line threading $x_0 + \Delta x$. The timing difference between the arrivals in the ionosphere is
\[ \Delta t_i = \Delta t \left[ 1 + v_{BBF} \frac{d}{dx} \sqrt{\mu_0 \rho} \right] \]  

Let \( v_{AS} \) be the apparent speed of the Alfvénic wave front in the ionosphere. The above calculation gives

\[ v_{AS} = \frac{\tilde{v}_{BBF}}{1 + \tilde{\lambda} \cdot v_{BBF}} \]  

where \( \tilde{\lambda} = \sqrt{\mu_0 \nabla \left( \sqrt{\rho} \right)} \) and the tilde denotes the mapped BBF speed in the ionosphere.

If plasma mass contained in a flux tube is conserved in convection, \( \rho \propto V^{-1} \), giving \( \lambda \propto d \sqrt{V} / dx \). Since \( V \) generally decreases toward Earth, \( \lambda < 0 \). Equation (2) suggests that \( v_{AS} \) is larger than the mapped BBF speed, i.e., supra-kinematic.

If \( v_{BBF} \) is greater than the scale speed \( |\tilde{\lambda}|^{-1} \), the auroral streamer actually reverses direction and propagates poleward. What this means is that the Alfvén transit time on the outer field line is sufficiently long (due to the lower Alfvén speed or longer field lines, or both) that waves there arrive later in the ionosphere, although they were launched earlier, than waves on inner field lines. Equation (2) explains both the high speed of auroral streamers and the reversed poleward motion when \( v_{BBF} \) is sufficiently high.

We use the plasma sheet model of Wang et al. [2004] to calculate \( \lambda \) in (2), and the results are presented in Figure 3a, for different parameters. For a given \( v_{BBF} \), the intervals where \( v_{BBF} > |\tilde{\lambda}|^{-1} \) are the regions of flow reversal. We use a simplified BBF model in which the flow burst is assumed to maintain a constant speed between \(-25 \) and \(-15 \) \( R_E \) and then linearly decrease to zero between \(-15 \) and \(-8 \) \( R_E \). Figure 3b gives the time of
arrival of Alfven fronts for $v_{BBF} = 300$, 400, and 500 km/s, for the three instances of the model shown in Figure 3a. Apparent poleward motion occurs where the arrival curve has the abnormal slope $d\Gamma / dt > 0$, where $\Gamma$ is the magnetic latitude. Take the case highlighted in Figure 3b ($\Phi_{pc} = 68$ kV and $v_{BBF} = 400$ km/s) as an example. The poleward motion occurs in the range 67.6° to 68.1° ML, and this gap is closed in about 6 s, consistent with the observations given in the previous section. Note that streamer reversal is sensitive to $v_{BBF}$, as $v_{BBF} = 300$ km/s does not produce streamer reversals.

4. Discussion

The origin of the detached blobs preceding the counter-streaming in Figure 2 is not explained by the theory presented in the previous section. Liang [2004] proposed that, in a typical midtail reconnection event, a fast mode wave with phase speed $v_F$ is generated in addition to the flow burst with speed $v_{BBF}$. In general $v_F > v_{BBF}$, and the fast mode will be in front of the BBF. In general, the fast mode does not couple strongly to the ionosphere, hence leaving little trace in the ionosphere. However, as the fast mode runs against an increasing Alfven speed profile, eventually it will resonantly couple into Alfven modes which are visible as aurora. This behavior is qualitatively consistent with the detached blobs. In the 960402 event reported by Nakamura et al. [2001], the appearance of auroral streamers is more than 1 min ahead of the Geotail observation of bursty bulk flows. This time delay is consistent with the above scenario, which will be elaborated in a separate work.

A major distinction of the present study is the high time resolution of the THEMIS ASI. The features of interest are short-lived (<10 s). Only the 3-s THEMIS ASI cadence
allowed us to see discriminating details. The high spatial resolution (1 km) also reveals details that seem to be at variance with the standard model. The two flow channels in Figure 2 are shown to be distinct, not only from their spatial separation, but also their time history. The width of the flow channels is narrow, less than 0.5° MLT. For a longitudinal mapping factor of ~50, this would map to an equatorial length of less than 0.3 \( R_E \). This is in contrast to the 1-3 \( R_E \) flow channel width deduced from statistical compilation of single satellite data. This discrepancy warrants further investigation.

Our interest in this paper is the first seconds of auroral streamer formation. As alluded to in the introduction, the global context of the 45-s interval can be described as a SMC state. Under this condition, sporadic reconnection is believed to occur in the mid tail, but no substorm is triggered. We reiterate that the predominant direction of auroral motion observed in the 1-h window in Figure 1 is equatorward. While bright equatorward moving aurora suggests that large-quantities of energy are transported into the inner magnetosphere, no substorm (and ensuing poleward expansion) is observed. In fact the THEMIS ASI and other ground-based instruments have captured in unprecedented detail how the injected energy is transported and dispersed. This will be the subject of a separate paper.

There is evidence to substantiate the claim that the high-latitude activations shown in Figure 1 are ionospheric signatures of the midtail reconnection. The steady pre-activation equatorward motion of the precipitation boundary and strong bipolar motion afterward is supportive of this view. Again, the 3-s THEMIS ASI data contain tantalizing details on the formative of the suspected reconnection. Due to length limitation, these details will again be deferred to a future study. It goes without saying that the upcoming in-situ data
from THEMIS spacecraft will be crucial to proving our claim here.

5. Conclusions

Our interest in this paper has been the study of the formation of isolated auroral streamers. We were able to obtain the first high-resolution observation (both in time and space) of fast auroral streamers in an optically dark auroral oval, and a series of arguments and calculations showing that the observed motion is consistent with the BBF concept but only under a revised theoretical framework that deviates from the commonly accepted PWC theory. The highlights of the study are:

1) Auroral streamers do occur spontaneously near the poleward precipitation boundary as largely isolated events. These forms move very fast in space. The formative stage is rapid and has transient features lasting <10 s.

2) The streamers observed on April 15, 2006 occurred in pair and in rapid succession. The pair were spaced by ~1° in longitude, much thinner than estimates from space-borne imagers. The estimated flow channel width is merely a fraction of Earth radius in the magnetotail.

3) The streamers moved fast, probably faster than the mapped BBF speed in the ionosphere. In a latitudinal range of ~1°, they showed a pattern of converging motion (poleward in lower latitudes and equatorward in higher latitudes). The apparent reversal from earthward BBFs, coupled with the clear absence of ionospheric convection speed anywhere close to that of the streamers, suggests that the standard PWC theory of BBF is inconsistent with the observation.

4) We proposed that, rather than being a bulk motion of mass and flux tube, auroral
streamers are optical signatures of Alfvénic fronts launched by earthward moving BBFs. This theory successfully reproduced the supra-kinetic motion of the streamers, and for sufficiently high BBF speed, reversed poleward streaming between two regions. For reasonable magnetospheric parameters, we reproduced from the magnetospheric model of Wang et al. [2004] the merging of the lower and upper parts of the streamer in a time of several seconds.

A final word should be said about the power of THEMIS ASI. Not having a spectral capability makes the camera not ideally suited for detailed studies where information about the precipitating particles is needed. As a morphological tracker, however, the THEMIS ASI is unrivalled, with a time resolution (3 s) and spatial resolution (1 km) more than an order of magnitude better than imagers mounted on orbital platforms. This paper demonstrates the potential of the astounding details possible with THEMIS ASIs. The research possibilities opened by the 3-s imaging data, in the THEMIS era is unparalleled.

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**Figure Captions**

Figure 1. Keogram of the 630 nm (red) line emission for the NORSTAR MSI in Fort Smith, between 07:00 and 08:00 UT. The green boxes mark the PBI onsets. The arrow identifies the event analyzed in detail in this paper.

Figure 2. High-resolution 3-s data are used to show the details of streamer motion and evolution. The three sub-events discussed in the text are circled with solid (1), dashed (2), and bold dotted (3) circles. The first circle of the same style marks the beginning of the sub-event, and the second circle the end. Poleward striation to form narrow flow channels is clear seen in sub-events 2 and 3.

Figure 3. Plot a: The $\lambda$ parameter according to the model of *Wang et al.* [200*], for cross-tail potential drops of 38 (black), 62 (red), and 86 kV (green). Plot b: Time of arrival of Alfven fronts for a BBF extending from $-25$ to $-8$ $R_E$, for $v_{BBF}$ values of 300, 400, and 500 km/s (as marked). Colored lines corresponds to the three cases of Wang et al. model in Figure 3.
Streamer reversal region