Observation of isolated high-speed auroral streamers and their interpretation as optical signatures of Alfvén waves generated by bursty bulk flows

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[1] The THEMIS All-Sky Imager at Fort Smith, Canada observed a sudden appearance and subsequent evolution of auroral streamers on April 15, 2006. The event took place in an oval that was optically dark, and evolved into a 20-minute period of intense equatorward streaming of red aurora. We characterize the incipient event as isolated streamers, a phenomenon previously linked with bursty bulk flows in the plasma sheet. Thanks to the high time and spatial resolution of THEMIS ASI, the observed streamer reveals some detailed features hitherto not reported. Aside from their exceptionally high speed and fine transient structures, the 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. **Citation:** Liu, W. W., et al. (2008), Observation of isolated high-speed auroral streamers and their interpretation as optical signatures of Alfvén waves generated by bursty bulk flows, *Geophys. Res. Lett.*, *35*, L04104, doi:10.1029/2007GL032722.

1. Introduction

[2] Auroral streamers are north-south aligned structures that usually have an apparent equatorward motion in the oval, and have been associated with the Bursty Bulk Flows (BBF) [*Nakamura et al.*, 2001; *Kauristie et al.*, 2003; *Sergeev et al.*, 2004; *Zesta et al.*, 2006]. 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 midtail reconnection. 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 liftetime less than 10 s. Existing space-borne imagers 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.* [2008] for details).

[3] 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 event under study reveals some puzzling features that defy the standard explanation, with poleward streaming that joins equatorward streaming from a poleward boundary intensification to form a complete flow channel. The observations are best reconciled by linking streamers to the propagation of Alfven wave front launched by BBFs. The revised theory predicts ‘‘super-kinematic’’ streamers 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.

2. Auroral Streamer Event on 15 April, 2006

[4] On 15 April, 2006, between 07:32:30 and 07:36:00 UT, the THEMIS GBO ASI at Fort Smith (60°N, 248°E geographic) 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 at a few nT for roughly 40 minutes (data not shown). WIND and ACE observations indicate a sudden northward turning of IMF at roughly 07:32 UT.

[5] In Figure 1, we present the keogram of the 630 nm red line from the NORSTAR multispectral imager (MSI) co-located with the THEMIS ASI in Forth Smith. The keogram has a 30-s time resolution and covers 07:00 – 08:00 UT. The red line emission is assumed to originate from a height of 180 km. At approximately 07:05 UT, there is a pseudo-breakup that fades in about 5 minutes. At 07:18, there is a poleward boundary intensification. The 630 nm emission expands both poleward and equatorward (referred to as bifurcating motion) for about 7 minutes. After 07:25 UT, there is a lull of activity until another PBI at 07:31:30. Again, the poleward boundary exhibits a steady equator-

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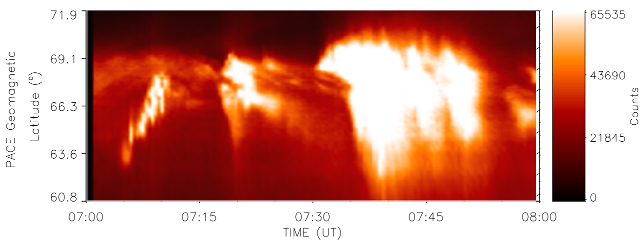

Figure 1. Keogram of the 630 nm (red) line emission for the NORSTAR MSI in Fort Smith, between 07:00 and 08:00 UT. The event analyzed here is the first faint streamer from the third onset.

ward movement prior to the activation, and a bifurcating motion of aurora follows after the brightening. Unlike the previous activation, the second PBI leads to a long-lasting (>20 min) series of equatorward moving streamers; the duration is consistent with the recent estimate of the average BBF lifetime by *Cao et al.* [2006]. At the time of the event, the Geotail satellite was at about $x = -26\ R_E$ but out of the current sheet. The CARISMA and THEMIS GBO magnetometers observed strong geomagnetic perturbations consistent with an enhancement of field-aligned currents. The global context of the 1-h window is the subject of a separate study currently in progress. Here we focus on a small slice of the event (Figure 1), and its detailed evolution seen by the THEMIS ASI at Fort Smith (Figure 2). 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 end of sub-events we would like to highlight. Sub-event 1 starts at 07:33:48 UT. The first evidence of brightening is detected at magnetic latitude $\sim 68.5°$ and magnetic longitude $-54.5°$ at 07:32:15 UT (not shown), 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 striation from the primary activation region extends equatorward, so does the detached blob, with the two never fully establishing 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 $\sim 0.5°$ equatorward, giving an average speed of 3.6 km/s. The detached blob begins to fade 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 ($\sim 0.5°$ 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 moves equatorward and those connected to the low-latitude luminosity moves *poleward*. Within 2 frames (6 s), the counter-moving streamers have covered a distance about 1°, giving a relative speed of ~ 18 km/s. Sub-event 3 immediately follows 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 $\sim 1°$, giving a closing speed of ~ 12 km/s, and carves out a separate flow channel about $\sim 1°$ MLT east of the channel formed by sub-event 2. We thus conclude that poleward auroral streamers are not observational oddities.

[6] We have examined the SuperDARN observation. There is no intersecting beam coverage over Fort Smith, but the westernmost beam 0 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 400 m/s to 1,100 m/s towards the radar. While the jump is consistent with the observation of the streamers, the LOS speed is a far cry from the inferred auroral streamer speed.

[7] 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 and poleward striation are related to the primary activation. In the following section, we offer a plausible explanation to substantiate this view.

3. Theoretical Interpretation

[8] According to the plasma bubble model of BBF [*Chen and Wolf*, 1999, and references therein], it is assumed that streamers are the ionospheric footprint motion of underpopulated flux tubes. The footprint motion in the simulation of *Chen and Wolf* [1999] is slow, taking tens of minutes to traverse the plasma sheet. In contrast, the formation of flow channels in sub-events 2 and 3 are fast, consummated in less than 10 s. Depending on the magnetic field model used, the latitudinal mapping factor at $\sim 68°$, can range from 300 to 1000. Using the lower limit, an ionospheric speed of 10 km/s corresponds to 3000 km/s in the equatorial plane. Although flow bursts in excess of 1000 km/s are occasionally observed in the magnetotail, the majority of such events are under this threshold. Therefore, the streamer event of 15 April 2006 is likely super-kinematic, with speed higher than the mapped speed of its proposed BBF source. What is even more perplexing is the counter-streaming observed in the 2006-04-15 event. *Chen and Wolf* [1999] noted that the ionospheric footprint motion of a plasma bubble is always equatorward in their simulation, even though its magnetospheric motion could recoil in later stages.

[9] When a flux tube experiences a rapid reconfiguration such as a BBF, the ionospheric and magnetospheric motions are partially decoupled, because motions caused by inductive electric fields are not conveyed 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 Alfven waves generated by BBFs 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 interacts with its surrounding, and Alfven waves are launched from the head of the burst (see *Chen and Wolf* [1999] for a linear analysis). 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 ~ 1, meaning that the field-aligned currents carried by the incident and reflected waves reinforce each other. Accord-

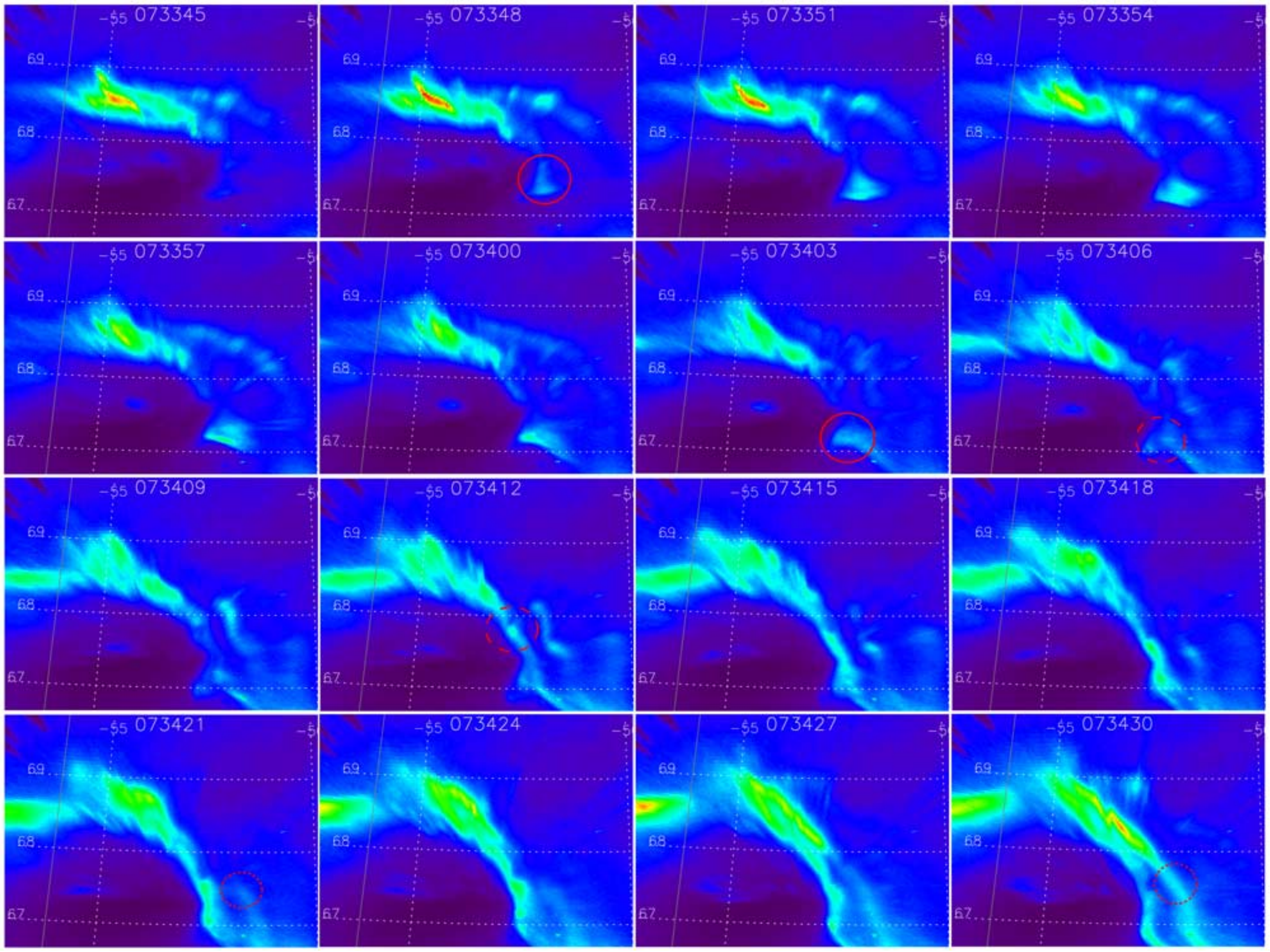

Figure 2. High-resolution 3-s data are used to show the details of streamer motion and evolution. The three sub-events discussed in the text are circled with solid (1), dashed (2), and bold dotted (3) circles. The latitudinal lines are 70° and 68° magnetic latitude. The solid vertical line is 23 h magnetic local time.

ingly, we expect the head of an auroral streamer to be accompanied by strong field-aligned currents (hence auroral luminosity) and relatively slow convection.

[10] For an Alfven wave front created at time t_0, the traveling time to the ionosphere is $t_A = \int ds/v_A = \sqrt{\mu_0 \rho} \int ds/B = \sqrt{\mu_0 \rho} V$, where ρ 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. In reality, the plasma density in the exosphere increases toward Earth; however, since the Alfvén speed is very large in this region, incorporation of a more accurate density model would introduce a negligible correction to our calculation. At time $t_0 + \Delta t$, the head of the flow burst is at $x_0 + v_{BBF}\Delta t$. 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

$$\Delta t_i = \Delta t \left[1 + \sqrt{\mu_0}\, \mathbf{v}_{BBF} \cdot \nabla\left(\sqrt{\rho} V\right)\right] \tag{1}$$

Let v_{AS} be the apparent speed of the Alfvénic wave front in the ionosphere. Equation (1) implies

$$v_{AS} = \frac{\tilde{v}_{BBF}}{1 + \vec{\lambda} \cdot \mathbf{v}_{BBF}} \tag{2}$$

where $\vec{\lambda} = \sqrt{\mu_0} \nabla(\sqrt{\rho} V)$ 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., super-kinematic.

[11] If v_{BBF} is greater than the scale speed $|\lambda|^{-1}$, the auroral streamer actually reverses direction and propagates poleward. What this means is that the Alfven transit time on the outer field line is sufficiently long 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.

[12] We use the plasma sheet model of *Wang et al.* [2004] to calculate λ in (2), and the results are presented in Figure 3a, for different parameters. For a given v_{BBF}, the intervals where $v_{BBF} > |\lambda|^{-1}$ are the regions of streamer reversal. We

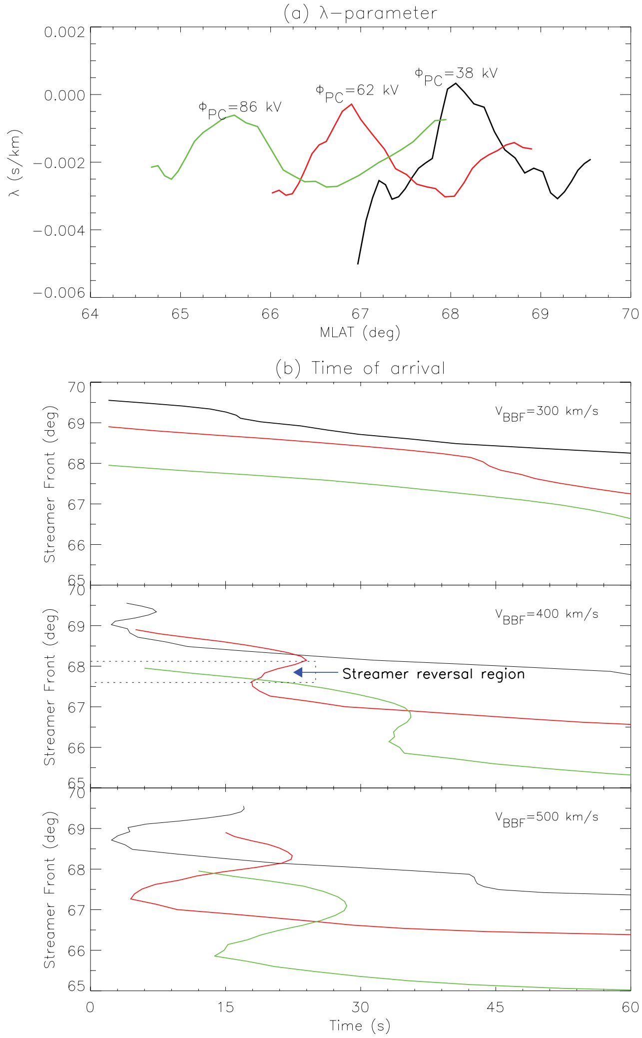

Figure 3. (a) The λ parameter according to the model of *Wang et al.* [2004], for cross-tail potential drops of 38 (black), 62 (red), and 86 kV (green). (b) Time of arrival of Alfvén fronts for a BBF extending from -25 to -8 R_E, for v_{BBF} values of 300, 400, and 500 km/s (as marked). Colored lines correspond to the three cases of the Wang et al. model in Figure 3a.

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 $v_{BBE} = 300$, 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 Γ is the magnetic latitude. Take the case highlighted in Figure 3b (Φ_{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 8 s, consistent with the observations given in section 2. Note that streamer reversal is sensitive to v_{BBF}, as $v_{BBF} = 300$ km/s does not produce streamer reversals (Figure 3b, top).

4. Discussion

[13] 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}. Reconnection theory predicts that $v_F > v_{BBF}$, and the fast mode should be in front of the BBF. The fast mode does not couple strongly to the ionosphere, hence leaving little trace in aurora. However, as it runs against an increasing Alfven speed profile, eventually the fast mode will resonantly couple to the Alfven modes which are visible as aurora. This behavior is qualitatively consistent with the detached blobs. *Nakamura et al.* [2001] reported that auroral activations typically precede Geotail observations of flow bursts by a few minutes, and adjustment for local time reduces this delay to ±1 min. This time delay is consistent with the above scenario. Using the red curve in Figure 3b (middle) as an example, we estimate from the observed delay between the detached blob and formation of flow channel in Figure 2 that the fast mode speed is ~600 km/s, reasonable for the midtail.

[14] The features of interest are short-lived (<10 s). Only the 3-s THEMIS ASI cadence allowed us to see the 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.

5. Conclusions

[15] We have reported on the formation of isolated auroral streamers observed on April 15, 2006. The observation is consistent with the BBF concept but only under a revised theoretical precept, namely the streamers are signatures of Alfven waves from a moving source. Because of Alfven transit time difference, streamer speed depends on both the motion of the BBF and the magnetospheric configuration. We summarize the highlights of the study as follows:

[16] (1) Auroral streamers can occur spontaneously near the poleward precipitation boundary as largely isolated events. It appears that streaming features have a "gestation" period of ~1 min from the onset of PBI, before they spread rapidly equatorward on a time scale ~10 s.

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

[18] (3) The streamers moved fast, probably faster than the mapped BBF speed in the ionosphere. Between ML 67° and 68°, 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 streamers are not convective in nature.

[19] (4) We proposed that auroral streamers are optical signatures of Alfvénic fronts launched by earthward moving BBFs. This theory successfully reproduced the super-kinematic motion of the streamers, and for sufficiently high BBF speed, reversed poleward streaming between roughly 67° and 68°. For reasonable magnetospheric parameters, we reproduced from the magnetospheric model of *Wang et al.* [2004] the connection of the lower and upper parts of the streamer in a time of several seconds.

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