Longitudinal development of a substorm brightening arc


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Abstract. We present simultaneous THEMIS-ground observations of longitudinal (eastward) extension of a substorm initial-brightening arc at Gillam (magnetic latitude: 65.6°) at 08:13 UT on 10 January 2008. The speed of the eastward arc extension was ∼2.7 km/s. The extension took place very close to the footprints of the longitudinally separated THEMIS E and D satellites at ∼12 RE. The THEMIS satellites observed field dipolarization, weak earthward flow, and pressure increase, which propagated earthward from E to D at a speed of ∼50 km/s. The THEMIS A satellite, located at 1.6 RE earthward of THEMIS E, observed fluctuating magnetic field during and after the dipolarization. The THEMIS E/D observations suggest that the longitudinal extension of the brightening arc at substorm onset is caused by earthward flow braking processes which produce field dipolarization and pressure increase propagating in longitude in the near-earth plasma sheet.

Keywords. Magnetospheric physics (Auroral phenomena; Plasma sheet; Storms and substorms)

1 Introduction

Substorms are fundamental disturbances in the magnetosphere and the polar ionosphere of Earth, but their onset mechanism is still a matter of some controversy. The auroral substorm originally defined by Akasofu (1964) shows a brightening of an auroral arc in the nightside auroral zone, and this brightening arc might be a manifestation of the processes causing the onset of magnetospheric substorms. The recent development of high-resolution cooled Charge Coupled Devise (CCD) cameras have made it possible to observe small-scale structures of brightening auroral arcs at substorm onset. Donovan et al. (2006a) reported a brightening arc which consisted of beads propagating eastward with a wavelength of ∼100 km. Liang et al. (2008) studied eight events of longitudinal wave structures of the brightening arc and concluded that the longitudinal wave number ranges between 100 and 300 (wavelength of ∼50–150 km). These papers suggest that the observed longitudinal waves correspond to the magnetospheric instabilities which are responsible for the substorm onset in the near-earth plasma sheet.

Liang et al. (2008) also found that the intensification of the brightening arc occurs within ∼10 s over an arc segment extending to approximately 1 h magnetic local time (longitude). The speed of the longitudinal expansion of the brightening arcs has some implications for the investigation of the onset mechanism. In the relevant literature, the speed varies from 1 km/s to more than 10 km/s (e.g., Solovyev et al., 1997; Yagou et al., 2005, 2007; Shiokawa et al., 2005; Sakaguchi et al., 2009). Angelopoulos et al. (2008) reported the simultaneous observation of a westward traveling surge (westward speed of 1 MLT/min ∼14 km/s) with the THEMIS satellite in the source plasma sheet. However, it is necessary to perform more simultaneous observations of the longitudinal development of brightening arcs using ground observatories and magnetospheric satellites since there are few examples of such observations.

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Fig. 1. Mosaic auroral images showing the auroral brightening at the substorm onset, which were obtained at three THEMIS all-sky imaging stations (from left to right, Whitehorse, Fort Smith, and Gillam) at 1-min intervals between 08:07:00 UT and 08:15:00 UT on 10 January 2008. Yellow, red, and green circles indicate the footprints of THEMIS D (58.7° N, 267.1° E), E (58.7° N, 264.3° E), and A (57.8° N, 267.3° E), respectively.

During 2–15 January 2008, we made THEMIS-ground campaign observations at two auroral-zone stations in Canada. Two 30-Hz sampling all-sky TV cameras (Shiokawa et al., 1996) and two ∼1-s sampling narrow field-of-view (FoV) cameras were installed at Gillam (56.4° N, 265.4° E, dipole geomagnetic latitude (MLAT): 65.6°) and Fort Smith (60.0° N, 248.1° E, MLAT: 67.0°). As an initial result of the campaign, we present observations of a longitudinally extending brightening arc performed simultaneously on the ground and by the longitudinally separated THEMIS satellites in the near-earth plasma sheet.

2 Observations

During the campaign period of 2–15 January, the THEMIS satellite was above the Canadian sector at postmidnight local times, while the substorm brightenings most frequently started in the premidnight sector. This configuration allowed for the longitudinal development of the brightening arcs at substorm onset to be observed both on ground and with the THEMIS satellites. In this paper, we focus on one such event observed on 10 January 2008. Although the event was first identified using our 30-Hz all-sky TV camera at Gillam, in this paper we use auroral images from the THEMIS all-sky imager (ASI) array, which has a sampling period of 3 s (Donovan et al., 2006b; Mende et al., 2008), since the development of the brightening arc was rather slow at Gillam while the THEMIS ASI array provided a wider view of the auroral development over the central and the eastern parts of Canada.

Figure 1 shows mosaic auroral images taken at 08:07–08:15 UT (01:47–01:55 LT at Gillam) at 1-min intervals at Whitehorse (left), Fort Smith (center), and Gillam (right) on 10 January 2008 during an auroral brightening event. The footprints of THEMIS A, D, and E are shown with green, yellow, and red circles, respectively. These footprints were calculated for the respective locations of the satellites at 08:10 UT by using the Tsyganenko-96 geomagnetic field model (Tsyganenko, 1995). Ambiguities of a few degrees in latitude are expected from the field-line mapping at different interplanetary parameters. The effect of field-aligned current may cause longitudinal shift of the footprint (e.g., Donovan, 1993; Donovan et al., 2008).
The auroral brightening event occurred at Fort Smith at 08:08:00 UT, after which it immediately extended westward toward Whitehorse at 08:09:00–08:10:00 UT. On the other hand, the eastward extension toward Gillam was much slower, lasting from 08:10:00 UT to 08:14:00 UT. The arc extending eastward reached the footprint of THEMIS E (red circle) at ~08:13:00 UT and of THEMIS D (yellow circle) at ~08:14:00 UT. After 08:15:00 UT, the extension of this arc ceased, and it did not develop further on a global scale. The AL index calculated from the THEMIS GBO magnetometers decreased by ~70 nT between 08:06 UT and 08:14 UT. Coherent Pi2 pulsations and a weak positive bay (a few nT) were observed starting at 08:05 UT at the low-latitude THEMIS GBO magnetometers in North America.

Figure 2 shows auroral images corresponding to the areas near the THEMIS footprints at 08:13:00–08:14:00 UT expanded from Fig. 1. Although the eastward edge of the arc extending eastward was not clearly defined, the arc reached the THEMIS E footprint (red circle) at ~08:13:00 UT and the THEMIS D footprint (yellow circle) at ~08:14:00 UT. Since the separation of the two footprints was 162 km, the velocity of the eastward extension was estimated to be ~2.7 km/s (~162 km/60 s).

Figure 3 shows the locations of the THEMIS A, D, and E satellites in GSM coordinates at 08:10 UT on 10 January 2008. The THEMIS E and D satellites were at nearly the same X and Z location, being separated by ~1 R_E only in Y_GSM direction at a radial distance of ~12 R_E. THEMIS A was ~1.6 R_E earthward of THEMIS E at a radial distance of ~9.9 R_E. Note that at the ionospheric altitude, THEMIS A (green) was at the same longitude as THEMIS D (yellow). Thus, the brightening arc extension from THEMIS E toward THEMIS A/D in Figs. 1 and 2 maps to the eastward (minus Y_GSM) and earthward (plus X_GSM) propagation of some corresponding structure in the magnetosphere in the bottom panel of Fig. 3.
Fig. 4. Magnetic field, bulk flow velocity, magnetic, thermal, and total pressures, and ion density and temperature as obtained by the THEMIS A (green), D (blue), and E (red) satellites at 08:00–08:30 UT on 10 January 2008. The magnetic field and the flow velocities are in GSM coordinates. Only the magnetic field data were available for THEMIS A.
Figure 4 represents the magnetic field, the bulk flow velocity, the magnetic and thermal pressures, and the ion density and temperature as observed by the THEMIS E (red), D (blue), and A (green) satellites at 08:00–08:30 UT on 10 January 2008. The data regarding the magnetic field and the plasma were obtained with the fluxgate magnetometer (FGM) (Auster et al., 2008) and with the electrostatic analyzer (ESA) (McFadden et al., 2008), respectively. In this regard, the ESA data from THEMIS A were not available for the plotted interval. The vertical dashed lines at 08:13:00 UT and 08:14:00 UT indicate the timings when the arc extending eastward reached the footprints of THEMIS E and D, respectively.

Since the $B_x$ and $B_z$ intensities are comparable, and since the thermal pressure is much larger than the magnetic pressure ($\beta > 1$), the THEMIS E and D satellites were located in the plasma sheet near the equatorial plane. Furthermore, $B_z$ is the major component for THEMIS A, indicating that THEMIS A was also near the magnetospheric equatorial plane. Note that $B_x$ decreases for all satellites and finally reverses its sign at ~08:30 UT, indicating a northward motion of the magnetosphere. This motion starts around the same time as the velocity perturbations at ~08:06 UT.

About 1 min before the arc reached its footprint, THEMIS E observed a field dipolarization (an increase in both $B_z$ and $B_{total}$), and a weak earthward flow with a peak of ~50 km/s starting at 08:12:00 UT. This timing difference of 1 min might be due to the Alfvén transit time from the magnetosphere to the ionosphere. The magnetic pressure $P_M$ increased at this time, and the thermal pressure $P_{th}$ and the total pressure $P_{tot}=P_M+P_{th}$ also increased at 08:12:00–08:13:00 UT and maintained high values throughout the plotted interval. Similar features of field dipolarization, weak earthward flow, and increase in magnetic and thermal pressures were observed with THEMIS D starting at ~08:14:00 UT, with a more gradual trend. If we take the timing difference of 2 min between THEMIS E and D into account, the 1-$RE$ difference of these two satellites gives an earthward propagation speed of ~50 km/s. The magnetic field data of THEMIS A show a local dipolarization at 08:14:00 UT, nearly simultaneously with THEMIS E. Then, the magnetic field fluctuates rapidly on a time scale of the order of 10 s.

### 3 Summary and discussion

In this paper, we report simultaneous observations of a longitudinal (eastward) extension of a brightening arc at substorm onset at 01:50 LT on 10 January 2008, both on the ground and by the THEMIS A, D, and E satellites. We found that the magnetospheric source region of the brightening arcs extending eastward at THEMIS E and D corresponds to the field dipolarization, the weak earthward flow, and the pressure enhancement, which propagate with a speed of ~50 km/s in the magnetosphere at a radial distance of ~12 $RE$. THEMIS A at 9.9 $RE$ observed a dipolarization, although the magnetic pressure remained the same. Instead, THEMIS A observed a fluctuating magnetic field after the dipolarization.

The features observed by THEMIS E and D are to be expected if the satellites are located just earthward of the flow braking region (Shiokawa et al., 1997, 1998). The braking causes field dipolarization earthward of the braking region through the downward inertia current. The earthward compression of the field and the pileup of the dipolar field carried by the earthward flow also cause field dipolarization and enhancement of the magnetic pressure. The earthward injection of plasma causes the enhancement of the thermal pressure (e.g., Kistler et al., 1992; Miyashita et al., 2009). Thus, the present observations suggest that the brightening aurora extending in longitudinal direction was caused by the earthward flow and its subsequent braking.

The speed of the eastward extension as determined by the two THEMIS satellites was ~50 km/s. This velocity is much slower than the local Alfvén velocity (~400 km/s for a density of 0.3 cm$^{-3}$ and a magnetic field of 10 nT during the event on 10 January 2008), and is of the same order as the observed bulk flow velocity. This fact is also consistent with the idea that the flow braking caused the observed longitudinal extension of the brightening arc. However, we can not distinguish whether the braking occurs sequentially from the THEMIS E longitude to the THEMIS D longitude, or the observed westward flow (~20 km/s) during and before the dipolarization at THEMIS E corresponds to the change of the flow direction from earthward to eastward caused by the braking.

It is interesting to note that during the first dipolarization at 08:12 UT, the THEMIS E observed a concurrent increase in $B_z$ component. This may imply tailward current generation associated with a development of azimuthal (westward) pressure gradient. Such a development of westward pressure gradient is seen by comparing the pressures observed by THEMIS E and D at 08:12 UT.

It should be noted that the present observation does not separate the two substorm onset models, i.e., the reconnection at 20–30 $RE$ (outside-in model) and the current disruption/pressure reduction processes at ~10 $RE$ (inside-out model), because both processes generate earthward flows and their respective braking in the near-earth plasma sheet. The fluctuating magnetic field observed by THEMIS A might be an indication of current-driven instability which causes the tail current disruption at substorm onset (e.g., Lui et al., 1992), although the amplitude of the fluctuation is smaller than the intensity of the ambient field. It is interesting that THEMIS A observed the fluctuations at 9.9 $RE$ while THEMIS E and D at ~12 $RE$ did not. This suggests that the current disruption and the associated rarefaction occurring near THEMIS A caused the earthward flow and its braking at THEMIS D/E, although the maximum amplitude of the fluctuation was observed after the dipolarization.
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