



## Longitudinally propagating arc wave in the pre-onset optical aurora

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[1] We present the first systematic observational evidence for a traveling periodic structure in the pre-onset optical aurora – the longitudinally propagating arc wave (LPAW) – associated with flapping oscillations in the magnetotail. The LPAW is characterized by azimuthally moving intensity enhancements inside auroral arcs as seen by THEMIS ground-based all-sky imagers. It travels westward in the pre-midnight auroral sector during the 10–20 minutes preceding auroral breakup with a velocity of 2–10 km/s, time period 40–110 s, and wavelength 250–420 km. Magnetically conjugate measurements by THEMIS satellites show low frequency plasma oscillations consistent with the parameters of the arc wave in the course of current sheet thinning. When mapped into tail, wavelength (4800–9400 km) and velocity (70–190 km/s) of the LPAW are compatible with observations and theoretical predictions for current sheet flapping motions. Our results strongly suggest that LPAW is an auroral footprint of the drift wave mode (kink, sausage, ballooning, etc.) in a stretched magnetotail. **Citation:** Uritsky, V. M., J. Liang, E. Donovan, E. Spanswick, D. Knudsen, W. Liu, J. Bonnell, and K. H. Glassmeier (2009), Longitudinally propagating arc wave in the pre-onset optical aurora, *Geophys. Res. Lett.*, 36, L21103, doi:10.1029/2009GL040777.

### 1. Introduction

[2] Auroral arcs are a common auroral feature at higher latitudes. A number of studies have posited that there is likely a connection between the time evolving structure of auroral arcs and magnetotail dynamics. For example, attempts have been made to associate azimuthal structuring or beading of arcs around the time of substorm onset with the azimuthal structure of a magnetospheric instability [see, e.g., Roux *et al.*, 1991; Donovan *et al.*, 2008; Liu and Liang, 2009; Liang *et al.*, 2008; Rae *et al.*, 2009; Voronkov *et al.*, 1999]. Low frequency wave activity in the central plasma sheet (CPS) that could produce detectable optical signatures has been explored, both experimentally and theoretically, based upon *in situ* observations [Sergeev *et al.*, 2004; Voronkov *et al.*, 1999; Erkaev *et al.*, 2009; Golovchanskaya and Maltsev, 2005]. It has been proposed [Liang *et al.*,

2008] that the azimuthal arc structure observed around onset may be related to an instability occurring in a near-Earth CPS region, while longitudinally propagating patches of auroral luminosity could be a manifestation of MHD waves in the magnetotail [Safargaleev and Osipenko, 2001; Danielides and Kozlovsky, 2003]. However, despite recent efforts to find such a link, no one-to-one correspondence between wave processes in the optical aurora and in the magnetotail has been convincingly demonstrated so far.

[3] In this paper, we report the results of the first systematic quantitative analysis suggesting a direct connection between the low-frequency wave activity in the optical aurora and in the magnetotail. Based on the data provided by THEMIS mission [Angelopoulos, 2008; Donovan *et al.*, 2006; Bonnell *et al.*, 2008; Auster *et al.*, 2008], we show that during the last 10–20 minutes preceding the auroral breakup, the arcs tend to exhibit periodic azimuthally propagating fronts of optical intensity, hereby called the longitudinally propagating arc wave (LPAW). The speed and the direction of the pre-onset LPAW are consistent with the drift wave mode in a stretched magnetotail. The tail origin of the wave is confirmed by two conjunction studies showing simultaneous appearance of nearly identical wave patterns in the optical aurora and in the CPS.

### 2. Data and Methods

[4] We studied five representative substorm events (see Table 1) monitored by ground-based and *in situ* THEMIS instruments in February–March 2008. The events were selected based on the quality of optical data and the conjugacy of THEMIS satellites to the imager field of view (FoV). The arcs were studied close to the magnetic zenith, the slants of the arcs not exceeding 15 degrees relative to the latitudinal direction. The 03/03/08 event was observed by the THEMIS all-sky imager (ASI) at Fort Simpson; all other events were observed by the Gillam ASI. Both instruments operated with a 3 s sampling interval. The 110 km arc altitude corresponding to the typical peak emission height of keV electrons was chosen for all calculations.

[5] To focus on the dynamics of individual auroral arcs, we masked out the surrounding background. The position of the mask was determined manually once per minute, after which intermediate mask positions were computed using linear time interpolation. The spatio-temporal arc behavior was analyzed using the azimuthal (east-west) arc profiles, or ewograms [Donovan *et al.*, 2006], defined as  $a(\phi, t) = \langle I(\phi, \psi, t) \rangle_{\psi \in \Theta(\phi)}$ , where  $I$  is the local auroral intensity,  $\phi$  and  $\psi$  are respectively the magnetic longitude and latitude of the arc pixel,  $t$  is time, and  $\Theta$  is the range of latitudes occupied by the arc at a given  $\phi$ . Detecting LPAW in the ewogram is not straightforward because the arcs often contain large-scale inhomogeneities and undergo significant

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**Table 1.** Parameters of Longitudinal Arc Waves Shown in Figure 2<sup>a</sup>

mm/dd/yy	$t_w$	$t_{ons}$	$n$	$\tau$ , s	$v_y$ , km/s	$\lambda$ , km
03/03/08 S	7:49	8:04	10	$92 \pm 50$	$2.7 \pm 0.3$ (70)	250 (6100)
03/03/08 N	7:49	8:04	8	$108 \pm 34$	$2.3 \pm 0.1$ (90)	250 (9200)
03/05/08	5:53	6:04	9	$73 \pm 24$	$3.7 \pm 0.7$ (70)	260 (4800)
03/15/08 S	4:04	4:17	9	$79 \pm 60$	$3.7 \pm 0.5$ (90)	290 (7300)
03/15/08 N	4:07	4:17	6	$95 \pm 66$	$3.5 \pm 1.2$ (100)	330 (9400)
03/28/08	3:08	3:26	23	$44 \pm 33$	$9.7 \pm 2.6$ (190)	420 (8500)
Averages				$82 \pm 22$	$4.3 \pm 2.7$ (100)	$300 \pm 70$ (7500)

<sup>a</sup>Letters S and N correspond to northern and southern arcs in the double-arc systems (see text). Predicted magnetotail values (T89 mapping based on observed Kp value) are given in parentheses.

variations of the overall intensity. To reduce these effects and enhance the smaller-scale dynamics, the ewograms were detrended using spatiotemporal polynomial fit  $P(\phi, t)$  (5th order in space, 3rd order in time) computed for the entire studied domain of  $\phi$  and  $t$  values:  $A(\phi, t) = a(\phi, t) - P(\phi, t)$ . This procedure was tested on model signals containing no propagating wave fronts to make sure that it does not produce false signatures of LPAW. To improve LPAW visualization, the range of plotted  $A(\phi, t)$  values was adjusted on the case-by-case basis.

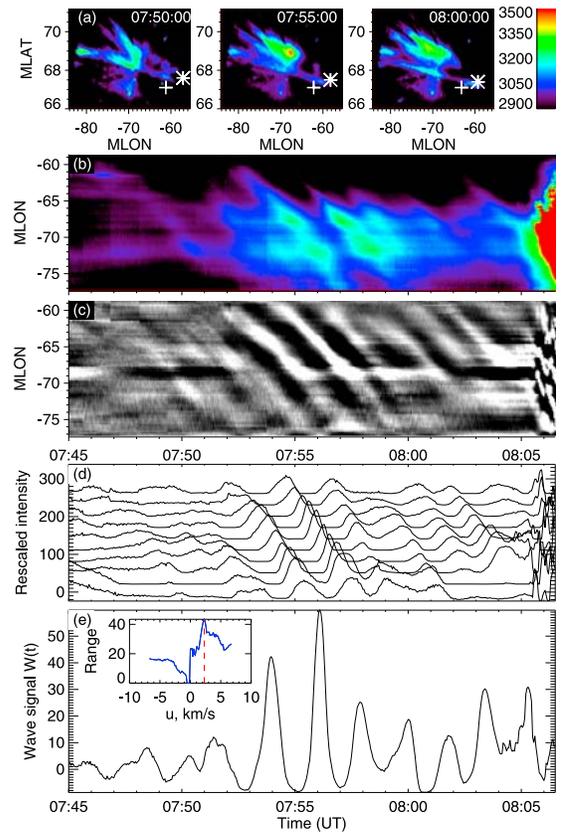
[6] For each substorm event, we identified the starting time  $t_w$  of the pre-onset LPAW activity as seen in  $A(\phi, t)$ , the substorm onset time  $t_{ons}$  estimated by the increase in the integrated auroral arc intensity, the LPAW duration  $T = t_{ons} - t_w$ , the number  $n$  of detectable wave fronts, the average longitudinal phase velocity  $v_y$  of the fronts, the wave period  $\tau = T/n$ , and the estimated wavelength  $\lambda = v_y T/n$ . The accuracy of velocity measurement was verified using the surfing average defined as  $w(t, u) = \langle A(\phi, t) \rangle_{\phi=ut}$ . In the presence of LPAW, the variance of  $w(t, u)$  has a maximum at  $u = v_y$  (averaging is done along the wave fronts, and the non-propagating optical noise is averaged out efficiently). Comparison of LPAW patterns with in situ plasma oscillations was based on the wave signal  $W(t)$  defined as the surfing average  $w(t, u = v_y)$  at the correct phase velocity. The amplitude signal-to-noise ratio of the low-frequency wave forms in  $W(t)$  was a least 4.0, which ensured statistically significant results despite the low intensity of LPAW signatures in the original data (in some cases <1% of the average arc intensity).

### 3. Results and Discussion

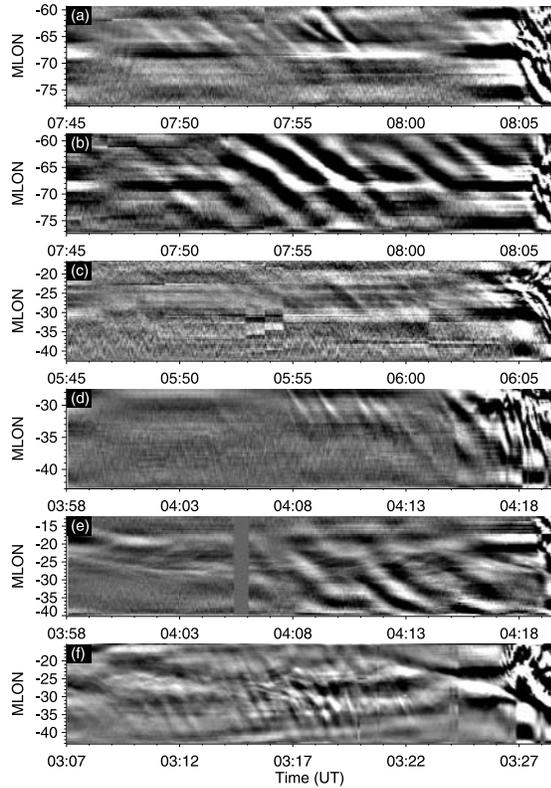
[7] Figure 1 provides an example of the detection of LPAW in a pre-onset arc observed at Fort Smith prior to the 08:04 03/03/08 substorm onset. The wave activity started about 15 minutes before the onset, and was found within the entire range of longitudes covered by the ground-based ASI. The wave propagated westward with  $v_y \approx 2.3$  km/s and  $\tau \sim 100$  s. Figure 2 shows detrended ewograms  $A(\phi, t)$  for the entire set of studied arcs, excluding the event of 02/13/08 which revealed no LPAW signatures. Each of the 03/03/08 and 03/15/08 events featured two growth phase arcs (northern and southern) which were studied separately.

The presence of LPAW – the westward traveling pre-onset wave – is evident in Figures 2a–2f.

[8] Technically, the frequency of the observed wave patterns (Table 1) falls into the range of Pi2 or Pc4 pulsations. It should be stressed that similar duskward propagating structures during the growth phase have been observed earlier [Voronkov *et al.*, 1999]. Ionospheric origin of this process is unlikely as it would require unrealistically strong convection electric field of  $\sim 200$  mV/m needed for primary wave modes in the high-latitude E-region [Kelley, 1989] to travel with the velocities shown in Table 1. This estimate exceeds by an order of magnitude the average zonal convection in the near-midnight ionosphere [Bristow, 2008], and is also well above the maximum measured values. The second region of interest, the acceleration zone located at the altitude of about 1–2 Re, contains much stronger electric fields which can, in principle, be responsible for an azimuthal motion of sub-arc structures consistent with the observed velocity range [Haerendel *et al.*, 1996]. This interpretation assumes strong velocity shears



**Figure 1.** (a) Sample images of the pre-onset aurora observed by the Fort Simpson ASI on 03/03/08. Ionospheric footprints of TH-C and TH-E are shown with stars and crosses, correspondingly. (b) Raw ewogram  $a(\phi, t)$  representing time evolution of the northern arc seen in Figure 1a. (c) Detrended ewogram  $A(\phi, t)$  exhibiting westward-propagating periodic fronts of auroral intensity. (d) Stack plot of time-varying auroral intensity at different magnetic longitudes ( $-70$  to  $-60$  MLon, bottom to top). (e) Wave signal  $W(t)$  extracted from  $A(\phi, t)$  using the surfing average technique. The inset shows the dynamical range of  $w(t, u)$  with a clear maximum at  $u = v_y = 2.3$  km/s.



**Figure 2.** Detrended ewograms of six growth phase arcs showing westward traveling wave patterns: (a) 03/03/08, southern arc; (b) 03/03/08, northern arc; (c) 03/05/08; (d) 03/15/08, southern arc; (e) 03/15/08, northern arc; (f) 03/28/08.

with oppositely directed azimuthal particle flows in the southern and northern portions of an arc. In contrast, the arc waves reported here maintain their westward direction for the entire range of latitudes covered by the arc. Although this argument does not exclude the involvement of the acceleration regions, it leads us to believe that the primary origin of LPAW is in a more remote part of the magnetosphere.

[9] The magnetospheric plasma sheet at the late substorm growth phase is a natural source of low-frequency fast-traveling plasma waves. The westward traveling arc waves can be a reflection of duskward propagating magnetospheric waves (often referred to as flapping current sheet waves), including kink, sausage, ballooning, and a variety of other drift-type (cross-field) modes in the tail [Erkaev *et al.*, 2009]. The wavelengths and the velocities of LPAWs shown in Table 1 are fully compatible with the observations and theoretical predictions for such waves [Sergeev *et al.*, 2004; Golovchanskaya and Maltsev, 2005].

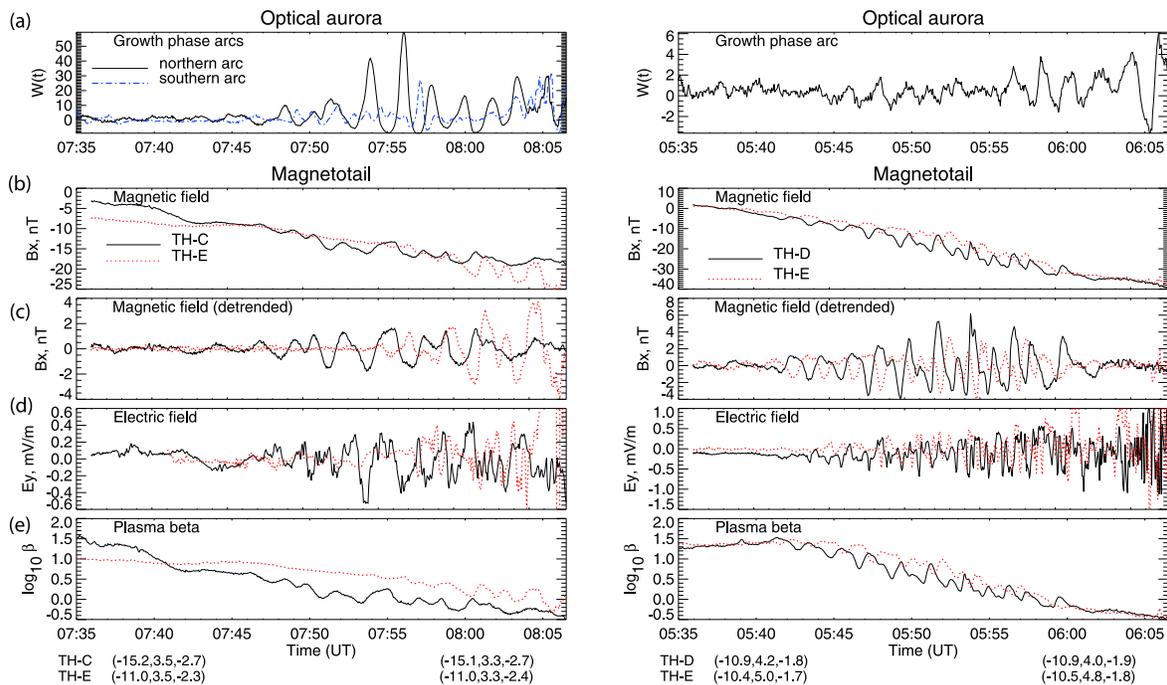
[10] Figure 3 presents two examples of simultaneous appearance of LPAW and low-frequency magnetotail oscillations supporting the proposed interpretation. In the 03/03/08 event, THEMIS-C (TH-C) spacecraft was in the mid-tail plasma sheet ( $x_{GSM} \sim -15$  Re), and it mapped within the FoV of the Fort Simpson ASI (see Figure 1). ULF wave oscillations of magnetic and electric fields [Auster *et al.*, 2008; Bonnell *et al.*, 2008], with a period of 2–3 minutes, were observed by this spacecraft. For the electric field, we used the spin fit data; the presence of the wave

signal was verified by using the waveform data. During the growth of the oscillation, the electric field was behind the magnetic field by about 1/4 period, which is consistent with the  $\pi/2$  phase shift prediction for drift plasma modes. We performed a minimum variance analysis (MVA) [Sonnerup and Cahill, 1967] of the TH-C magnetic field data during 07:40–08:04 UT. The three MVA eigenvalues are 0.60, 0.18, 0.016; the eigenvector corresponding to the smallest eigenvalue is  $-0.09\hat{x} + 0.80\hat{y} - 0.58\hat{z}$ , which shows that the tail wave features a dominantly azimuthal ( $y$ ) propagation front, in accordance with LPAW observations. The wave pattern was also observed in the southern arc (presumably mapped closer to the Earth than the northern arc), and on a near-Earth probe TH-E ( $x_{GSM} \sim -11$  Re). Due to the inherent limitation of the MVA, we could not determine the directionality of the wave (eastward or westward) for this event. In the 03/05/08 event, two near-Earth probes TH-D and TH-E were mainly separated in the azimuthal direction, and both observed conspicuous wave oscillations after 05:40 UT. We performed a cross-phase analysis on the  $B_x$  perturbations measured by the two probes, and obtained a propagation velocity of 90–100 km/s from TH-D to TH-E (i.e., westward). Mapping such a wave to the ionosphere using T89 model yields a velocity of  $\sim 4$  km/s, comparable with our LPAW estimate (see Table 1). Recently, Liu *et al.* [2008] have reported electric field oscillations at TH-E and TH-D for the same event with a period of about 70 s starting  $\geq 10$  min before the local onset, in agreement with our analysis.

[11] Both tail waves seen in Figure 3 were most evident when the satellites underwent a transition from the CPS ( $\beta \sim 10$ ) to its boundary region ( $\beta < 1$ ) during the late growth phase, hinting an intimate relationship between the wave generation mechanism and the current sheet thinning process. Asano *et al.* [2004] found that the thin current sheet usually begins to evolve  $\sim 15$  minutes prior to the onset, the timing being roughly consistent with the emergence of LPAWs in our examples.

[12] Based upon the above evidence, it is tempting to conclude that the LPAW is an ionospheric manifestation of the azimuthally-propagating drift wave in the magnetotail. Such a wave may manifest itself in auroras in at least two ways. It is common that a drift mode (e.g., ballooning) may couple to an Alfvén wave [Golovchanskaya and Maltsev, 2005]; also, a drift compressional wave may modulate the loss cone and the precipitation flux of energetic particles [Tsutsumi, 1984]. The absence of measurable in situ signatures of wave activity for the 03/15/08 and 03/28/08 events (Figures 2d and 2f) may reflect mapping errors as well as its spatial localization as suggested by the behavior of plasma  $\beta$  in Figure 3. Many wave generation mechanisms proposed for the current sheet oscillations are highly contingent upon local parameters (current sheet thickness,  $B_z$  magnitude, etc.), and therefore spatial confinement of wave activity is expected. On the other hand, flapping tail motion is known to be a ubiquitous phenomenon not limited to substorm activity [Runov *et al.*, 2009], and so LPAW events in the optical aurora should be quite common.

[13] The westward propagation of LPAW fronts (Figure 2) can be specific to pre-midnight arcs studied here. Based on the properties of flapping oscillations [Sergeev *et al.*, 2004; Erkaev *et al.*, 2009], eastward LPAW propagation should be



**Figure 3.** Simultaneous low-frequency wave oscillations (a) in the optical aurora and (b–e) in the CPS as measured by THEMIS probes, prior to the substorm onsets of (left) 03/03/08 and (right) 03/05/08. GSM coordinates of the probes are shown below the plots.

more typical for the morning auroral sector. Indeed, we found two clear examples (to be published elsewhere) that feature eastward traveling LPAWs in the morning arcs. Another issue that needs to be handled with care is the slant of the arcs introducing an ambiguity in the interpretation of the wave propagation direction. This and other uncertainties inherent to optical observations will have to be addressed in future studies of LPAW.

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