



## RESEARCH ARTICLE

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## Special Section:

Fundamental Properties and Processes of Magnetotails

## Key Points:

- Equatorward propagating auroral FLR in the same location as substorm onset
- Field Line Resonances can be used to determine field line topology
- Field Line Resonance physics should be considered for triggering substorm onset

## Supporting Information:

- Figure S1
- Text S1
- Movie S1

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## Field line resonances as a trigger and a tracer for substorm onset

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**Abstract** In this paper, we show that periodic auroral arc structures are seen at the location of one particular auroral substorm onset for the 15 min preceding onset, suggesting that field line resonances should be considered a strong candidate for triggering substorm onset. Irrespective of whether this field line resonance is coincidentally or causally linked to this substorm onset, the characteristics of the field line resonance can be used to remote sense the characteristics of the geomagnetic field line that supports substorm onset. In this instance, the eigenfrequency of this resonance is around 12 mHz. Interestingly, however, there is no evidence of this field line resonance in a seven satellite major Time History of Events and Macroscale Interactions during Substorms (THEMIS)-GOES conjunction, ranging from geosynchronous orbit to  $\sim 30 R_E$ . However, using space-based cross-phase measurements of the local field line eigenfrequency at the inner THEMIS locations, we find that the local field line eigenfrequency is 6–10 mHz. Hence, we can reliably say that this 12 mHz Field Line Resonance (FLR) must lie inside of THEMIS locations. Our conclusion is that a high- $m$  field line resonance can both represent a strong candidate for a trigger for substorm onset, as first proposed by Samson et al. (1992), and that its characteristics can provide invaluable information as to where substorm onset occurs in the magnetosphere.

### 1. Introduction

The explosive release of energy within a substorm marks one of the most dynamic and vibrant auroral displays seen in the solar-terrestrial environment. Since the late 1950s, the relationship between the magnetic and auroral signatures observed from the ground during substorms has been studied qualitatively and the characteristics of the auroral substorm firmly established [e.g., Heppner, 1958; Akasofu, 1964, 1977]. However, a definitive scientific consensus regarding the physical mechanism or mechanisms that trigger this explosive energy release in space in the form of the magnetospheric substorm has yet to be reached. That magnetic flux is added to the nightside magnetosphere through dayside reconnection processes is well established, as is the closure of the flux via nightside reconnection. However, what process or processes lead to the initiation of the closure of this nightside flux is a specific topic of vigorous scientific debate [e.g., Lui, 1991; Angelopoulos et al., 2008; Lui, 2009; Angelopoulos et al., 2009].

Since the substorm term was first coined, a plethora of substorm onset mechanisms have been proposed to explain the initiation of the process. The two most common frameworks discussed in the literature involve the direct initiation of substorm expansion phase onset directly from Near-Earth Neutral Line (NENL) reconnection [e.g., Hones, 1976] or alternatively from a nearer-to-the-Earth plasma instability [e.g., Roux et al., 1991; Lui et al., 1991; Voronkov et al., 1997] that indirectly leads to a release of energy from reconnection only once the system has previously become unstable in the nearer-Earth region. However, it should be noted that there are many other viable physical frameworks within which to interpret substorm onset, all of which should still be considered to be candidate mechanisms as they have not been categorically ruled out despite decades of observations. These include the Boundary Layer Dynamics model [Rostoker and Eastman, 1987], Field Line Resonance destabilization of the Shear-Flow Ballooning Instability [e.g., Samson et al., 1992a], the near-Earth Geophysical Onset model [Maynard et al., 1996], the global Alfvénic interaction model [Song and Lysak, 2001], and magnetosphere-ionosphere coupling and feedback [e.g., Atkinson, 1970; Sato, 1978; Lysak, 1986, 1991] being related to a local reduction in field-aligned currents at the onset region [Murphy et al., 2012]. Additionally, there are also numerous variations on these core plasmaphysical frameworks. For example, Kepko et al. [2009] identified the first visual ionospheric signature of a flow burst prior to auroral onset consistent with the direct

triggering of substorm onset via flow bursts [e.g., Angelopoulos *et al.*, 2008] or flows initiating an instability closer to the Earth which then leads to auroral substorm onset [e.g., Nishimura *et al.*, 2010], onset defined in these cases as being the first visually identified sign of the brightening of the aurora. Ultimately, to distinguish between models, unambiguous causal sequences of events must be determined.

In this paper we address observations relating to one of these particular models, namely, the conclusion by Samson *et al.* [1992b], Samson [1994], and Samson *et al.* [1996] that field line resonant processes might be related to substorm expansion phase onset. Natural ultralow frequency (ULF) modes of the magnetosphere and Field Line Resonances (FLRs) have been studied for decades, from both observational [e.g., Samson *et al.*, 1971; Allan *et al.*, 1986] and theoretical [e.g., Southwood, 1974; Chen and Hasegawa, 1974] standpoints. Specifically, the action of the solar wind under a variety of guises can drive discrete frequency compressional ULF waves into the magnetosphere that drive discrete frequency FLRs [e.g., Kivelson *et al.*, 1984; Kivelson and Southwood, 1985; Lessard *et al.*, 1999; Mann *et al.*, 1999, 2002; Rae *et al.*, 2005, 2007a]. Magnetospheric FLRs are most often studied at dayside local times, where they can be prevalent on the flanks (often due to the Kelvin-Helmholtz instability) [e.g., Rae *et al.*, 2005, 2007a]. How FLRs directly relate to auroral arcs is not a trivial process. Certainly, FLRs can be shown to be linked to periodic auroral displays [e.g., Rae *et al.*, 2007b; Roldugin and Roldugin, 2008] and have been shown to be capable of modulating existing auroral arcs [e.g., Lotko *et al.*, 1998] or directly powering auroral displays [e.g., Rankin *et al.*, 2006, 2007]. However, FLRs have also been seen on the nightside, both in the ionosphere [e.g., Fenrich *et al.*, 1995] and in the magnetotail [e.g., Takahashi *et al.*, 1988; Nose *et al.*, 1998; Keiling *et al.*, 2003; Zheng *et al.*, 2006]. On the nightside, FLRs can still be excited on closed field lines in stretched and nonaxisymmetric magnetic field configurations [Allan and Wright, 1998; Mills and Wright, 2000; Mathews *et al.*, 2004; Russell and Wright, 2010], and fast-Alfvén mode coupling can also occur on very long field lines such as at the plasma sheet boundary layer [e.g., Allan and Wright, 1998]. Closed field line FLRs typically demonstrate poleward phase propagation [e.g., Fenrich *et al.*, 1995; Wright and Allan, 1996; Wright *et al.*, 1999]. However, equatorward phase propagation has also been postulated for FLRs in the vicinity of a localized energy source [e.g., Mann, 1998] which may be particularly pertinent to those associated with magnetotail physics, where a significant and localized energy source may be provided by the pressure gradients arising from the stretched nightside magnetic fields [e.g., Samson *et al.*, 1992a]. Equatorward phase propagation could also occur when the direction of the Alfvén frequency gradient is such that the Alfvén frequency increases with distance from the Earth, perhaps in the region closer to the inner edge of the plasma sheet where inner magnetospheric and central plasma sheet plasma can mingle. Substorms and FLRs were first postulated to be linked to each other by Samson *et al.* [1992b], both as a trigger for the explosive energy release and also to serve as a marker for the locale of substorm initiation in the magnetosphere. In the results presented here there is a clear temporal correlation, with an FLR being seen to immediately precede substorm onset, and its characteristics used to determine its magnetospheric location.

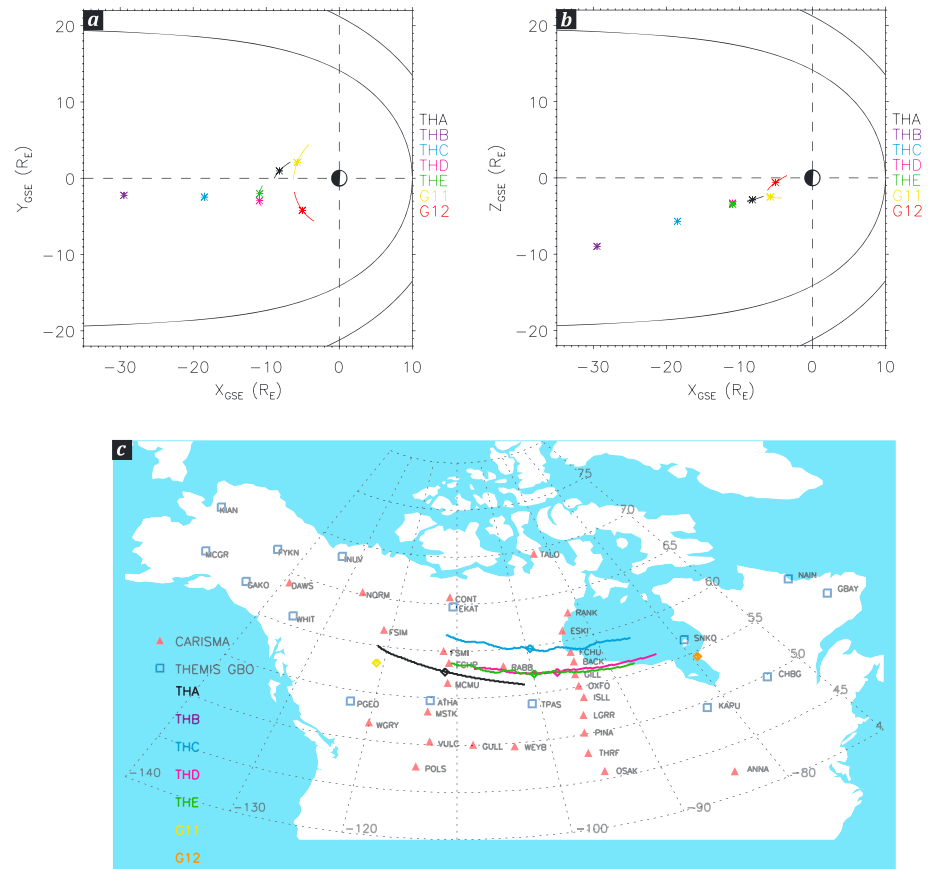
FLRs are a specific manifestation of ULF waves in the magnetosphere. The kinetic effects of the thermal electron interaction with FLRs lead to parallel electric field formation and acceleration of electrons [Rankin *et al.*, 2007]. In the nightside magnetosphere, theoretical studies [Samson *et al.*, 2003] demonstrate that these kinetic effects in low-frequency FLRs lead to periodic bands of aurora of limited latitudinal extent. These bands exhibit poleward and azimuthal motion, reforming periodically at the same frequency as the FLR. ULF waves have been demonstrated to be clearly associated with the substorm expansion phase [e.g., Jacobs *et al.*, 1964; Saito, 1969], although whether they may have a causal role in the processes leading to energy release at substorm onset remains controversial. Nightside ULF waves are typically taken to span the 1 s–200 s period range, but for historical reasons have been separated into two discrete period bands that are used to define differing quantities during the substorm expansion phase. ULF waves in the Pi1 band (1–40 s period) are traditionally used to study the specifics of the region of substorm onset [e.g., Bösinger and Yahnin, 1987; Arnoldy *et al.*, 1987; Bösinger, 1989; Takahashi and Liou, 2004], whereas ULF waves in the Pi2 (40–150 s period band) have been used to define elements of the substorm current wedge [e.g., McPherron *et al.*, 1973; Lester *et al.*, 1983; Murphy *et al.*, 2011]. However, through the analysis of the entire spectrum across the Pi1 and Pi2 bands, it has been shown that ULF waves can actually be used as a robust and reliable diagnostic for the time and location of auroral substorm onset and indeed for other auroral intensifications [e.g., Milling *et al.*, 2008; Mann *et al.*, 2008; Murphy *et al.*, 2009a, 2009b; Rae *et al.*, 2009a, 2009b, 2010; Walsh *et al.*, 2010; Rae *et al.*, 2011; Rae *et al.*, 2012].

The brightening (or formation) and subsequent breakup of the most equatorward auroral arc represents the auroral signature of substorm expansion phase onset [e.g., Akasofu, 1977]. Of course, in order to establish the field aligned current (FAC) of the substorm current wedge, one requires the propagation of an Alfvén wave which may also be reflected from the ionosphere, perhaps multiple times, to establish the FAC [e.g., Southwood and Hughes, 1985]. The relationship of such Alfvén ULF waves to the substorm process remains poorly understood, although this reflection and feedback from ionospheric reflection (or overreflection) [e.g., Lysak and Song, 2002] forms the basis of the ionospheric feedback substorm onset paradigm. In this paper, we demonstrate that the formation and intensification of the onset arc during a well-studied substorm event shares similar characteristics with auroral displays caused by standing ULF waves. Our analysis sheds light upon the onset process itself and highlights that long-wavelength ULF waves may provide a tracer for mapping substorm-related auroral displays to locations in the magnetosphere. Whether FLRs also have a role in triggering substorm energy release in the manner suggested by Samson *et al.* [1992a] requires further study, but for the event shown here there is no doubt that they are in very close correspondence and at the very least consistent with the expected association in the Samson FLR onset hypothesis.

## 2. Previous Studies: 29 January 2008

This event has been studied a number of times already by Lui *et al.* [2008a, 2008b], Mende *et al.* [2009], and Nishimura *et al.* [2010]. The event occurs during a major conjunction of the Time History of Events and Macroscale Interactions during Substorms (THEMIS) fleet and so provides a data-rich environment with which to study the physics of substorm onset. In each of these investigations listed above, a “substorm onset time” is defined based upon the visual inspection of the Fort Simpson, NT (FSIM, at 67.23° geomagnetic latitude and 294.41° longitude), and Fort Smith, NT (FSMI, at 67.29° geomagnetic latitude and 307.05° longitude), THEMIS All Sky Imagers (ASI) [Mende *et al.*, 2008] (see their Table 2 and Figure 5). Although all the onset times identified by different authors coincide to within 1 min, the different ancillary information presented in each study results in three different conclusions regarding the physics of the onset mechanism for this single substorm event. Lui *et al.* [2008a, Figure 2] show a summary of the ground-based optical data used to time the expansion phase onset. Using ground-based camera images 1 min apart, Lui *et al.* [2008a] estimate the onset time to be ~0742 UT and argue that the onset of dipolarization, flows, and particle energization evolve tailward during the event, pointing to a near-Earth initiated scenario for onset in this event. Mende *et al.* [2009] presented time-of-flight analysis of magnetic perturbations observed by the in situ THEMIS probes, which were assumed to be triggered by tail reconnection. From higher-cadence auroral images, Mende *et al.* [2009] note that the poleward expansion of the aurora occurs at ~07:42:42 UT for this event. These authors do caution that their 2-D time-of-flight timing analysis cannot reliably be used in this case study due to the azimuthal separation of the satellites and the ground-based data. Finally, Nishimura *et al.* [2010] list this event in their “PBI (poleward boundary intensification)-triggering-substorm” database taken solely from THEMIS ASI data. In the supporting information of Nishimura *et al.* [2010], the onset is identified as 0742 UT and was preceded by “preonset aurora” in the form of a PBI, which was identified in the northeastern field of view of the FSMI imager at 0738 UT (Y. Nishimura, private communication, 2012). For context, Nishimura *et al.* [2010] proposed that a PBI is the ionospheric signature of a fast earthward flow which subsequently may “trigger” a substorm if the flow reaches the inner magnetosphere. These “preonset” auroral signatures can be seen anywhere from greater than 15 min to 1 min prior to the signatures of breakup and poleward auroral arc motion at “onset,” with an average time between the PBI and a visual determination of substorm onset to be ~5.5 min.

This paper contains a further reanalysis of the same substorm event at ~0742 UT on 29 January 2008. By considering a longer time period surrounding onset, we show clear evidence of the physics that must be operating close to the magnetospheric initiation region of this substorm, that is, a small perpendicular-scale standing wave or high-*m* field line resonance. Substorm onset undulations are azimuthal striations that develop along a previously existing auroral arc [e.g., Rae *et al.*, 2010]. On the other hand, FLRs manifest as periodic formation, brightening, and propagation of individual arcs [e.g., Samson *et al.*, 1996]. Our observation is more similar to Samson *et al.* [1996] than Rae *et al.* [2010] in that the brightness of the auroral arc does not appear to vary in azimuth. Instead, the arc repeatedly brightens and propagates westward and equatorward, which is to be expected from a small azimuthal scale field line resonance and which produces azimuthal auroral forms as Elphinstone *et al.* [1995] first showed.

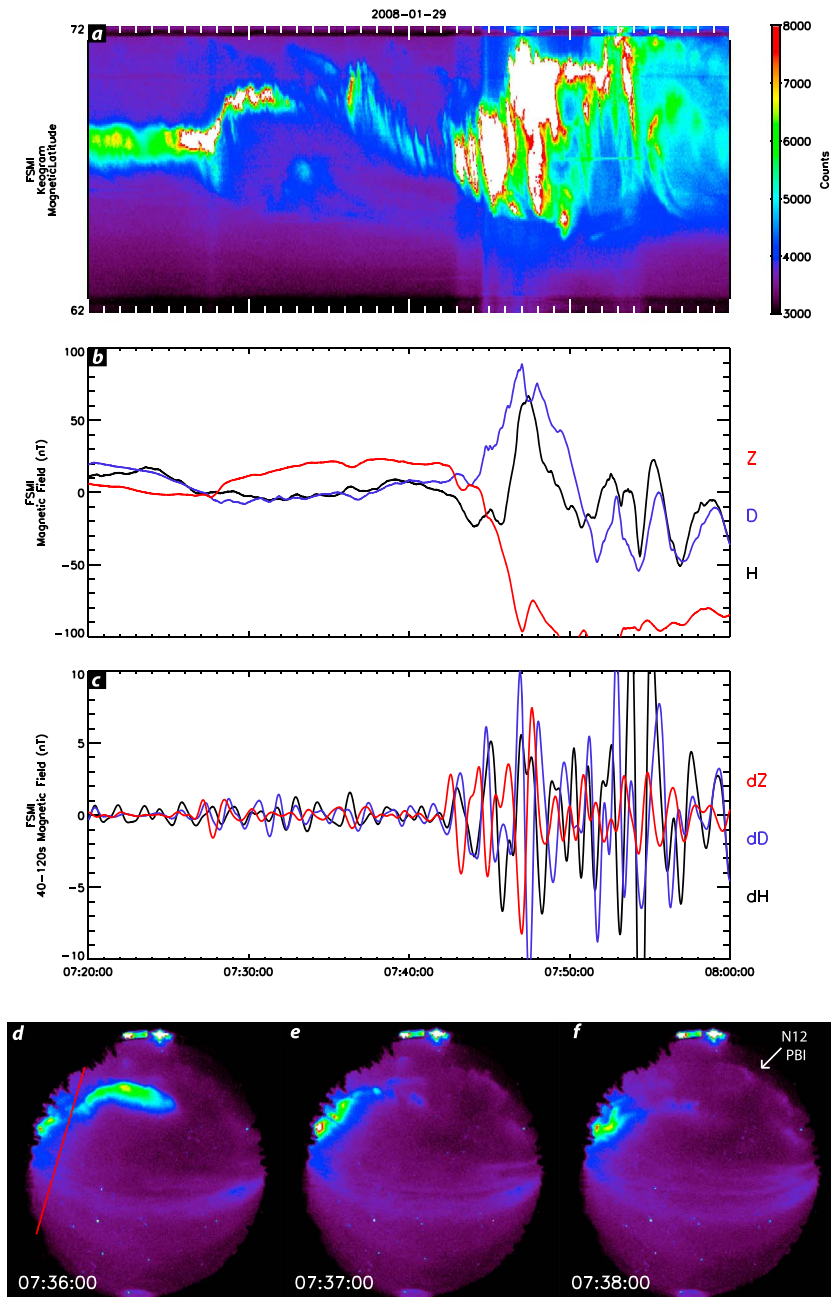


**Figure 1.** The locations of the THEMIS and GOES satellites in the (a) GSE X-Y plane and (b) GSE X-Z plane. (c) The predicted ground footprints using the T96 magnetic field model, with the ground traces between 0700 and 0800 UT, and the symbols denote the predicted ionospheric projection of the satellites at 0740 UT.

### 3. Additional Observations: 29 January 2008

Figure 1 shows the locations of the THEMIS and GOES satellites used in this study in (a) the GSM X-Y plane, (b) the X-Z GSM plane, and (c) the ionospheric projection of their footprints using the T96 magnetic field model [Tsyganenko, 1995]. Also shown in Figure 1c are the locations of the ground-based magnetometer and optical instrumentation across the North American continent. We use colocated measurements from the THEMIS FSIM and FSMI all-sky imagers (ASIs) [Mende et al., 2008] and the Canadian Array for Realtime Investigations of Magnetic Activity (CARISMA) FSIM and FSMI ground magnetometers [Mann et al., 2008], as did the previous authors studying this event, but in this paper we extend the time period studied in order to view the intriguing auroral configuration that forms well in advance of expansion phase onset. These auroral features can be seen in Lui et al. [2008, Figures 2 and 3], and the auroral onset are deemed to occur in the overlap region covered by both the FSIM and FSMI ASI fields of view (FOV).

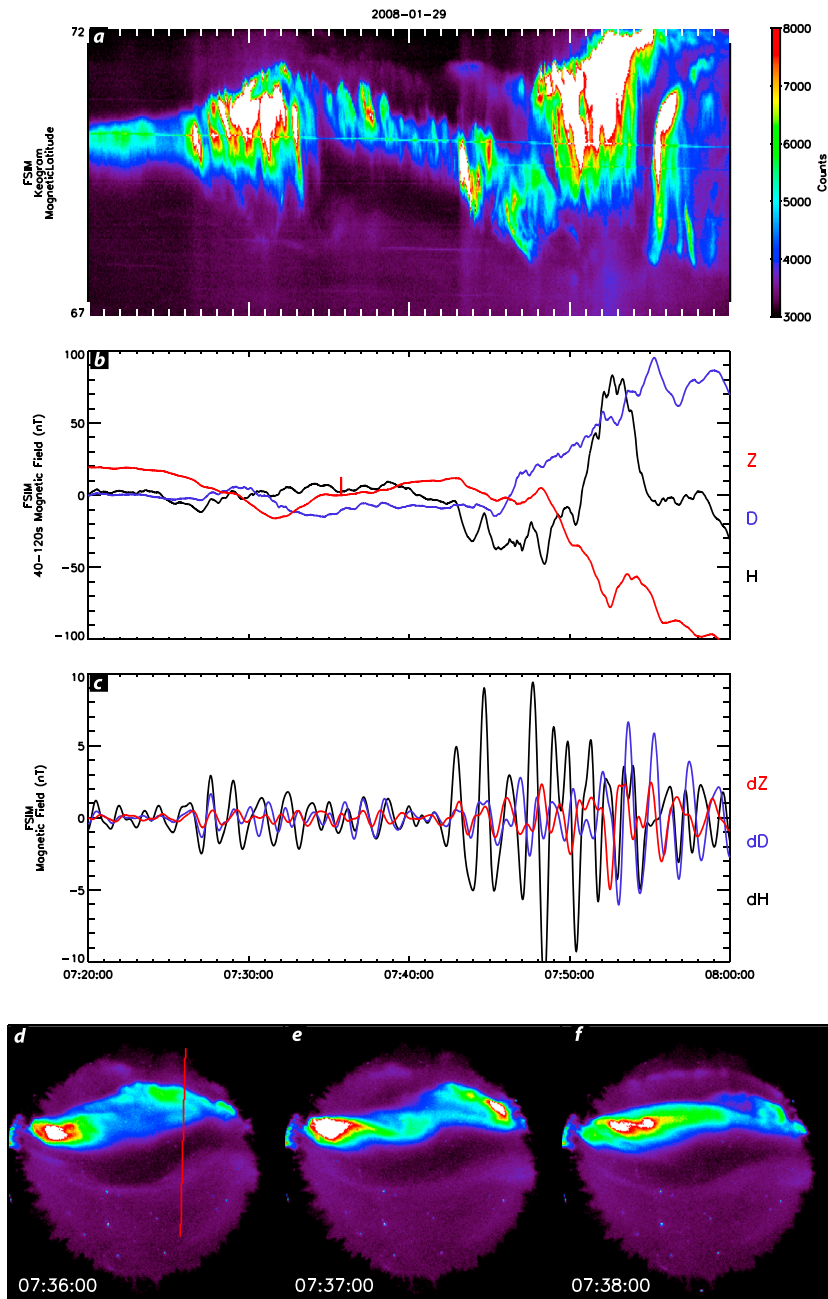
A summary of the auroral and magnetic ground-based measurements from the FSMI station is shown in Figure 2, and the measurements from FSIM are shown in Figure 3. Figures 2 and 3 show (a) a keogram computed in a direction perpendicular to the equatorward arc that breaks up and in the most western portion of the FSMI FOV (approximately in the geomagnetic north-south direction), followed by (b) the DC ground magnetic perturbations (c) 40–120 s period filtered magnetic perturbations, and (d–f) selected 2-D auroral images from the ASI during the interval, aligned approximately in the geographic coordinate system, the first panel of which shows the location and orientation of the keogram with a solid red line. Figure 2a shows the development of two auroral substorm onsets during the 0720–0750 UT period. We concentrate on the growth phase of the second activation, which can clearly be seen to be isolated from the first intensification in Figure 2a. The second auroral substorm onset is marked by brightening and poleward expansion of the aurora around 0742 UT and occurs after an extended period of equatorward motion of the aurora that initiates around 0730 UT.



**Figure 2.** An overview of the 29 January 2008 event from 0720 to 0800 UT from the THEMIS FSMI ASI and CARISMA FSMI magnetometer. (a) A north-south slice through the FSMI field of view, (b) the  $H$ ,  $D$ , and  $Z$  and (c) 40–120 s period filtered ground magnetic perturbations from the FSMI magnetometer, and (d–f) three selected images throughout the interval. The arrow marked N12 PBI denotes the *Nishimura et al.* [2010] PBI hypothesized to trigger this auroral substorm.

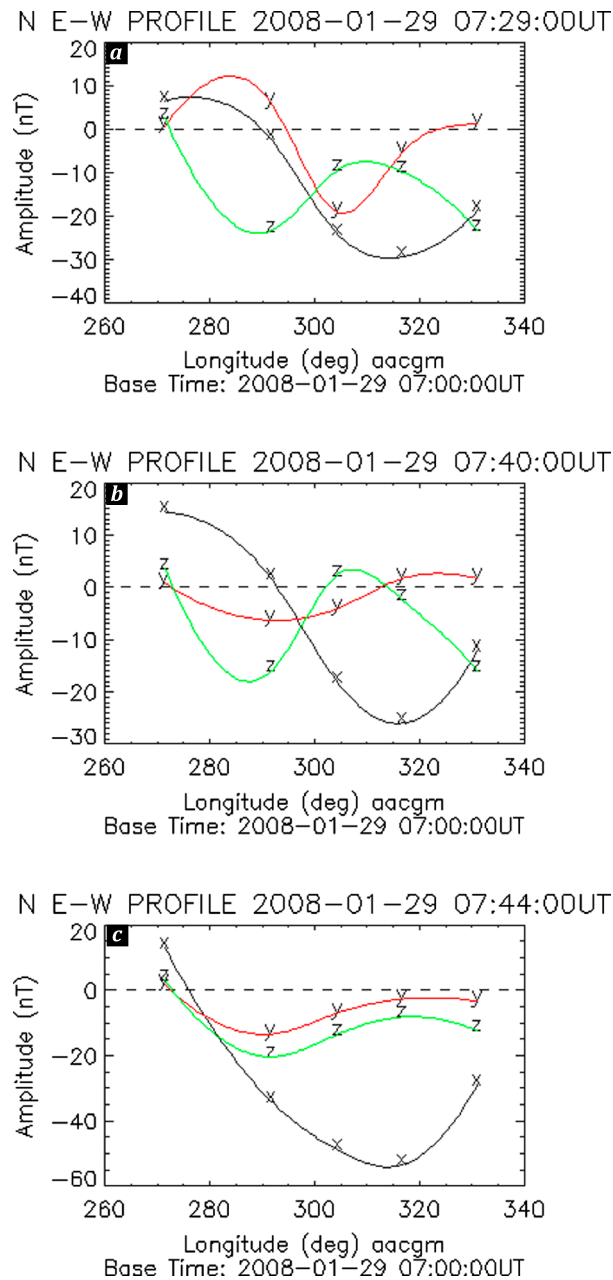
Note the clear periodic striping in the equatorward arc as the arcs move equatorward. From the magnetometer time series (Figure 2b), there appears to be a quiescent period from 0720 to 0740 UT, whereupon the geomagnetic bay starts to form. Only small magnetic perturbations are seen preceding the geomagnetic bay. Clear in Figure 2a is the presence of periodic equatorward moving auroral features that start around 70° latitude and progress equatorward toward substorm onset at ~0742 UT. The intensity of the auroral features is highly variable prior to onset.

Figure 3 shows a similar meridian scan from the FSIM ASI, this time to the east of the central meridian (keogram location again shown in Figure 3d). Again, two major auroral brightenings can be seen, the first



**Figure 3.** An overview of the 29 January 2008 event from 0720 to 0800 UT from the THEMIS FSM ASI and CARISMA FSM magnetometer in the same format as Figure 2.

around 0726 UT and the second around 0743 UT. Small magnetic perturbations can be seen between these auroral brightenings, but it is only at the start of the substorm expansion phase at ~0743 UT that the magnetic bay structure and Substorm Current Wedge (SCW) forms and large-amplitude ULF waves are observed. We emphasize that this paper will not present a specific discussion of the timing of substorm onset, as in *Lui et al.* [2008], *Mende et al.* [2009], and *Nishimura et al.* [2010]. Rather, we focus on the periodic auroral striping that is seen in both Figures 2 and 3 in the 15 min prior to substorm onset. Both Figures 2 and 3 show repetitive equatorward moving auroral forms that reappear with similar periods. In the following section, we present an analysis of these periodic auroral arcs close to the zenith of the FSM camera. We will show that these arcs correspond to the onset arc and investigate the interesting evolution of these arcs over a 15 min period prior to onset. We note that a weak (~4 nT peak to peak) low-amplitude magnetic perturbation is observed at the CARISMA

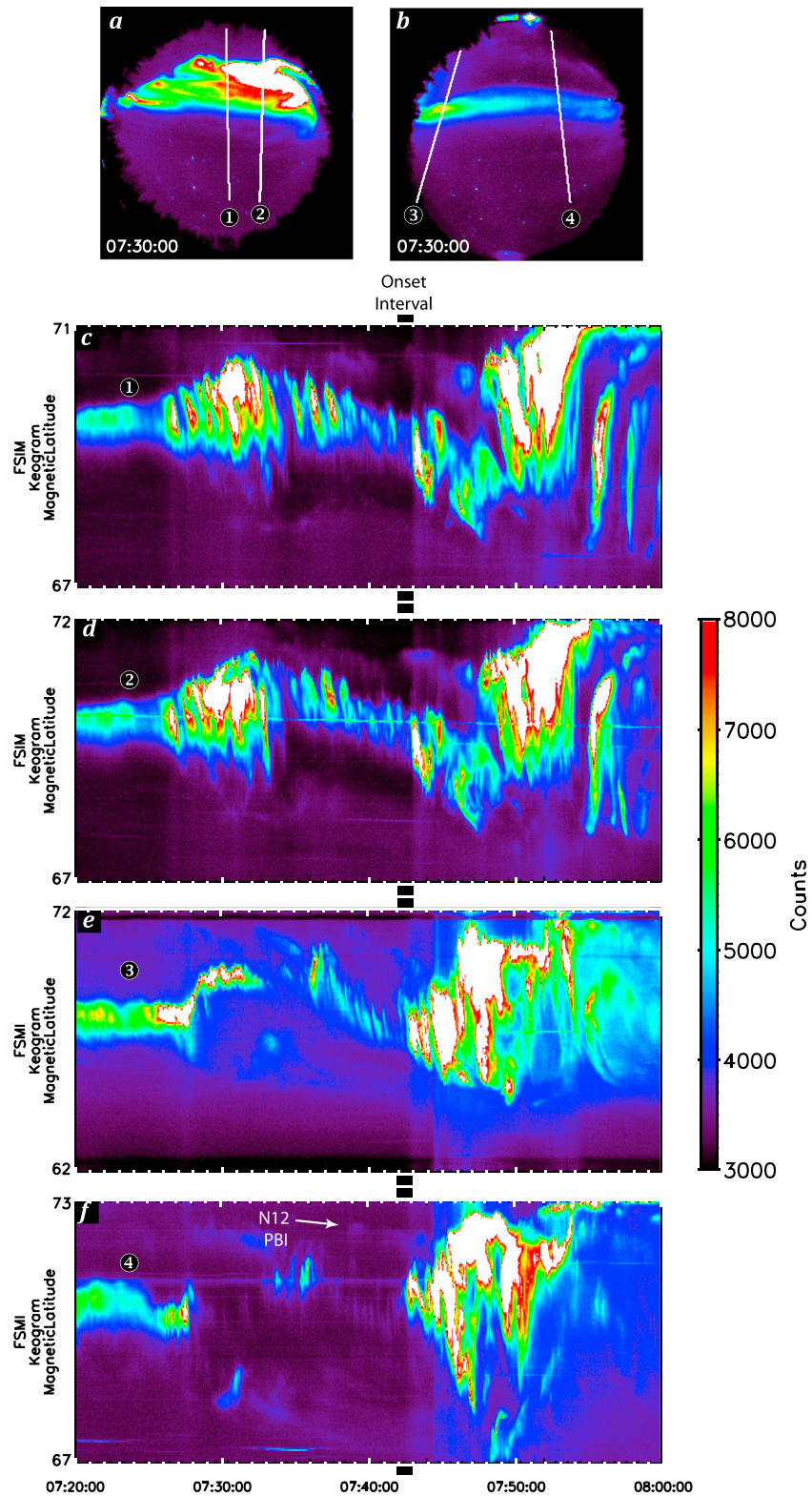


**Figure 4.** Three longitude profiles from the geosynchronous line of CARISMA magnetometers from (a) 0729 UT, (b) 0740 UT, and (c) 0744 UT, all baselined to 0700 UT. From right to left the stations are GILL-RABB-FSMI-FSIM-DAWS; the raw measurements are denoted by the x, y, z symbols, and spline fits to these measurements are shown by the black, red, and green curves, respectively.

FSIM and FSMI magnetometers that show evidence of an 8 mHz perturbation in both the *H* and *D* components. This is consistent with a heavily attenuated small spatial scale ULF wave primarily screened from ground-based magnetometers.

We use a combination of magnetometer and auroral measurements to determine some aspects of the location of this auroral FLR signature. Using ground-based magnetometers from the geosynchronous line of CARISMA magnetometers [Mann *et al.*, 2008], we determine the location of the FLR and substorm onset relative to the eastward and westward auroral electrojets and the interface region between them. This is achieved by use of longitude profiles of the CARISMA geosynchronous line (from east to west, DAWS-FSIM-FSMI-RABB-GILL in Figure 1c) *X*, *Y*, and *Z* magnetic measurements baselined to a quiet time preceding the interval of interest at 0700 UT. Using the idealized model of the electrojets shown in Rostoker and Friedrich [2005], an eastward electrojet corresponds to a positive *X* component, whereas a westward electrojet corresponds to a negative *X* component. Figure 4 shows longitude profiles at 3 times during the interval (a) at approximately the start of the interval that displays FLR-like behavior at 0729 UT, (b) the late growth phase at 0740 UT, and (c) the early expansion phase at 0744 UT. The interface between the eastward and westward electrojets, marked by the zero crossing of the *X* component magnetic field, is initially at or around the FSIM station (Figures 4a and 4b). At the onset of the expansion phase (Figure 4c), the interface region shifts one station (and approximately 1 h of magnetic local time (MLT)) to the west indicating that the westward electrojet has intruded further into the evening sector. The magnetic signature of the auroral surge form seen at 0745 UT in Figure 3g can be seen in the positive *y* component deflection at the FSIM station

in the Figure 4a. Note that we can also use the optical emissions from the THEMIS ASIs to estimate whether the FLR signature occurs equatorward of the poleward boundary of the auroral oval. Although the white-light THEMIS ASIs respond primarily to 5577A emissions and no definitive scientific consensus has been reached as to what the poleward boundary of 5577A represents, previous work has found that the poleward border of the 5577A emissions lies equatorward of the open-closed field line boundary in the dayside ionosphere [e.g., Murphree *et al.*, 1980]. Furthermore, since this process is shown subsequently to be resonant, the repetitive auroral signature must be on closed field lines. Since there are optical emissions to the north of this FLR signature,



**Figure 5.** North-south slices through the FSMI and FSIM ASI FOV. Figure 5 shows two representative ASI images from (a) FSMI and (b) FSIM at 07:30:00 UT, and (c–f) the locations of the keograms. Figures 5c–5f shows keograms from west of onset (through approximately the FSIM zenith), to 5° west of onset (through the eastern portion of the FSIM FOV), to the onset meridian in the FSMI FOV, and finally to the east of onset through the zenith of the FSIM FOV, as labeled 1–4 above. The arrow marked N12 PBI denotes the *Nishimura et al.* [2010] PBI hypothesized to trigger this auroral substorm that can be seen in Figure 2f.



**Table 1.** Onset Times for the 01-29-2008 Event According to the Literature, and Corresponding Physics Ascribed to the Process

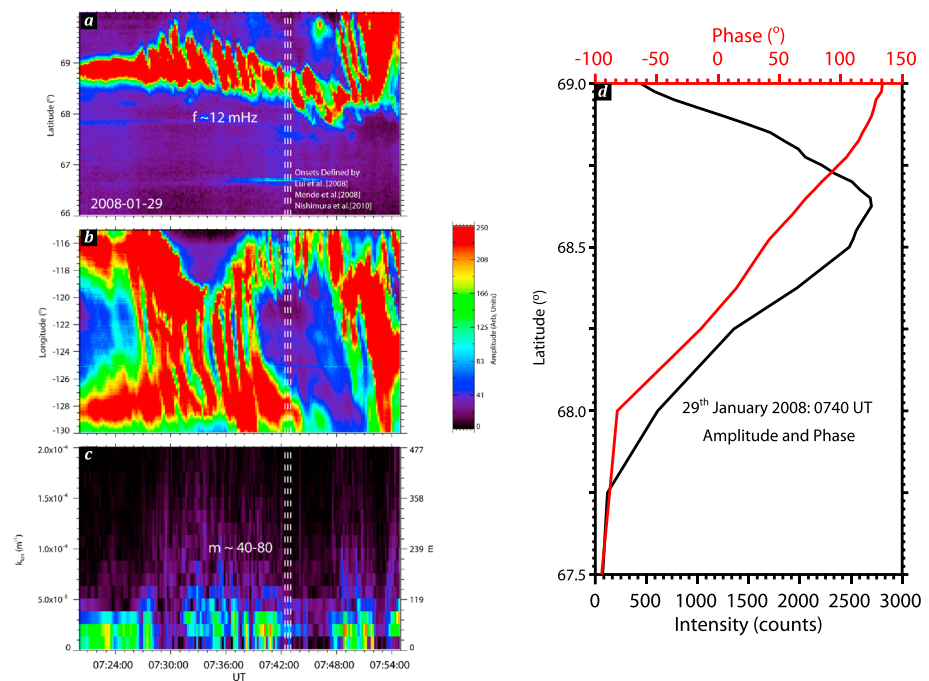
Study	Visually Determined Onset Time (UT)	Determination of Physics Operating Around Substorm Onset	First Time Linked to Substorm Onset
<i>Lui et al.</i> [2008]	0742	Instability provoking tail collapse Inside-out	
<i>Mende et al.</i> [2008a]	0743	Reconnection driven hypothesis Outside-in	
<i>Nishimura et al.</i> [2010]	0742	Flows destabilizing inner magnetosphere Outside-causing-in	0738 UT
<i>Rae et al.</i> [2013]	not available	Field line resonance	0720 UT

and the FLR itself must be standing between conjugate ionospheres, we conclude that the FLR lies within a closed field line region at the interface region between the eastward and westward auroral electrojets.

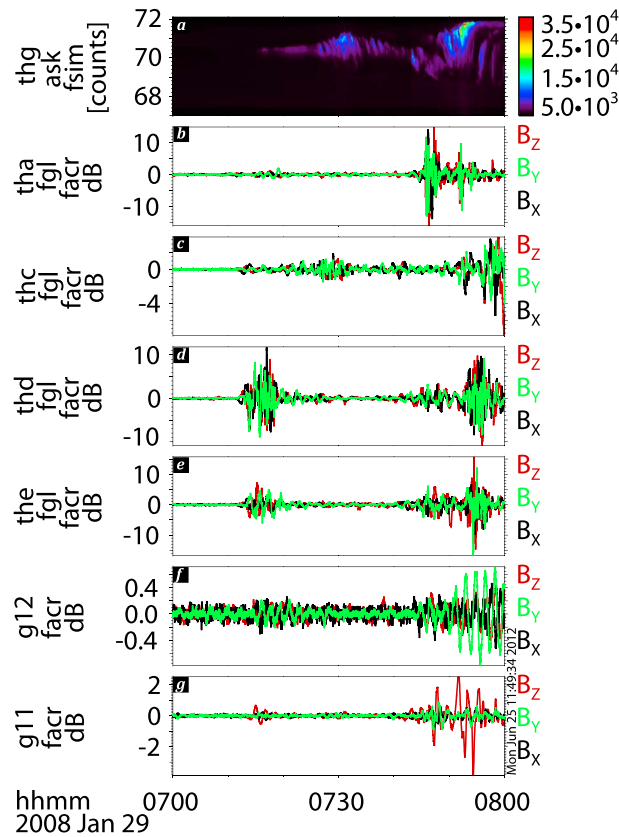
#### 4. Analysis of the Repeating Arc Generation Observed Before Substorm Onset

Figure 5 shows four north-south (keogram) slices through the FSIM (Figures 5c and 5d) and FSMI (Figures 5e and 5f) FOVs at approximately 5° of magnetic longitude separation and brackets the onset region. Three separate studies of this event have identified substorm onset between 0742 UT and 0743 UT (see *Lui et al.* [2008], *Mende et al.* [2009], and *Nishimura et al.* [2010] in Table 1). At 0738 UT in the north-east FOV of the FSMI imager, a PBI has been identified which is associated with the preonset sequence as described in *Nishimura et al.* [2010] (Y. Nishimura, personal communication, 2012). A movie of the FSMI and FSIM ASIs is provided in the supporting information.

Clear in both FSIM keograms is the formation and equatorward phase propagation of repeating auroral forms (Figures 5a and 5b) long before 0738 UT. Periodic auroral arc formation and equatorward phase propagation can also be seen in the FSMI FOV, but the arcs are not as bright as those propagating through the FSIM camera. The most obvious periodic striping in the onset meridian in the FSMI FOV (Figure 5c) is first observed around 0726 UT and continues throughout the period, though reducing in intensity. This is similar to the periodic arc generation seen in the FSIM ASI, where the period ~0728–0735 UT contains a bright auroral



**Figure 6.** Amplitude and phase profiles for the periodic (12 mHz frequency/83 s period) of the auroral display taken at 0740 UT, immediately prior to the independently defined auroral onset time. (a) The keogram from the central meridian of the FSIM ASI. (b) The intensity as a function of longitude and time along ~68.7° latitude. (c) The results of a spatial fast Fourier transform in longitude in order to estimate the azimuthal wave number of the auroral arc structuring as a function of time. (d) The three onset times are defined in the literature by three separate studies [*Lui et al.*, 2008; *Mende et al.*, 2008; *Nishimura et al.*, 2010]. Figure 6d shows the amplitude and phase profile of the 12 mHz component of the auroral FLR at 0740 UT.



**Figure 7.** Magnetic field perturbations taken from the THEMIS and GOES satellites transformed into field-aligned coordinates. In this coordinate system, Z denotes field aligned, Y denotes the azimuthal direction, perpendicular to  $R \times Z$  direction and positive eastward, and X makes up the right-handed set, and, in the equatorial plane, is directed outward in the direction of  $R$ . A background field determination of 200 s was applied.

substorm onset, the signal is periodic throughout the whole time interval up until onset. It is evident from Figures 3 and 5 that an amplitude peak and phase change is present in the aurora in the entire period 0730–0742 UT, and Figure 6d shows the latitudinal variation of the amplitude and phase of the 12 mHz auroral fluctuations at 0740 UT. There is strong amplitude peak as a function of latitude, across which there is a (greater than)  $180^\circ$  phase change across the auroral intensity peak, as expected for a classical FLR [e.g., Walker et al., 1979; Samson et al., 1992b]. Note that in contrast to the traditional externally driven poleward phase propagation observed [e.g., Fenrich et al., 1995; Fenrich and Samson, 1997; Samson et al., 2003; Rankin et al., 2005], the equatorward phase propagation is characteristic of a FLR driven by a localized energy source [e.g., Mann, 1998]. We note that Figure 6 shows that the FLR signature that breaks up is preserved at this meridian, and the auroral oval continues to expand equatorward, although in the more easterly meridians (see Figure 5e), the auroral intensification is already underway.

In summary, we have shown conclusive evidence that the repeated formation and structuring of the onset arc over a 20 min time interval is characteristic of a high- $m$  field line resonance. Recent work has suggested that faint auroral signatures of PBIs anywhere between 1 and 15+ min prior to substorm should be considered as a potential substorm onset trigger [Nishimura et al., 2010].

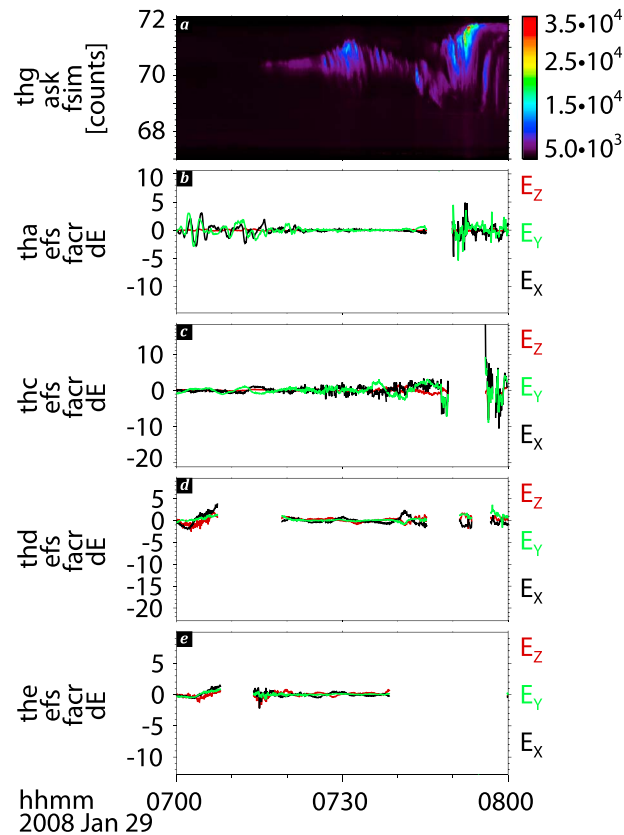
In the following section, we search for the magnetospheric counterpart to this FLR.

### 5. Where is the Magnetospheric Counterpart to This FLR?

The major conjunction of THEMIS spacecraft during this event provides an opportunity to look for the magnetospheric counterpart to the ground-based measurements for this FLR. We search for the signature of

display, and the 0735–0744 UT interval shows periodic auroral structuring at a lower intensity. East of onset, there is little evidence of periodic auroral arc generation and propagation, as evidenced by the second FSMI keogram (Figure 5f).

In order to determine the spatial and temporal characteristics of these auroral signatures, Figure 6 shows the latitudinal and longitudinal variation of the auroral fluctuations. Latitudinally, the FLR extends around  $1^\circ$  of magnetic latitude, from  $68$  to  $69^\circ$  initially, but gradually evolving equatorward during the substorm growth phase. Fourier analysis of the temporal variations of the aurora indicate that they have a frequency of  $\sim 12$  mHz or 83 s period (Figure 6a). Figure 6b demonstrates the longitudinal scale of the auroral forms that is much larger than the latitudinal scale shown in Figure 6a. Figure 6c shows the Fourier analysis of the spatial variation of the auroral forms in the longitudinal direction. The enhancements at  $\sim 2 \times 10^{-5} \text{ m}^{-1}$  would correspond to an  $m$  number of 40–80 at this latitude if the azimuthal periodicity were to continue around the Earth's circumference. As it is, this optical signature is highly localized such that only two periodic auroral forms are observed simultaneously at the same latitude. Although the auroral arc intensities dim immediately prior to



**Figure 8.** Electric field measurements taken from the THEMIS satellites and transformed into field-aligned coordinates in the same manner as described in Figure 7. Intervals where the third component of electric fields could not be calculated via  $E \cdot B = 0$  when the electric field vector is within  $\pm 15^\circ$  of the spin plane or during the rapidly varying magnetic fields during the substorm expansion phases are removed from the data set.

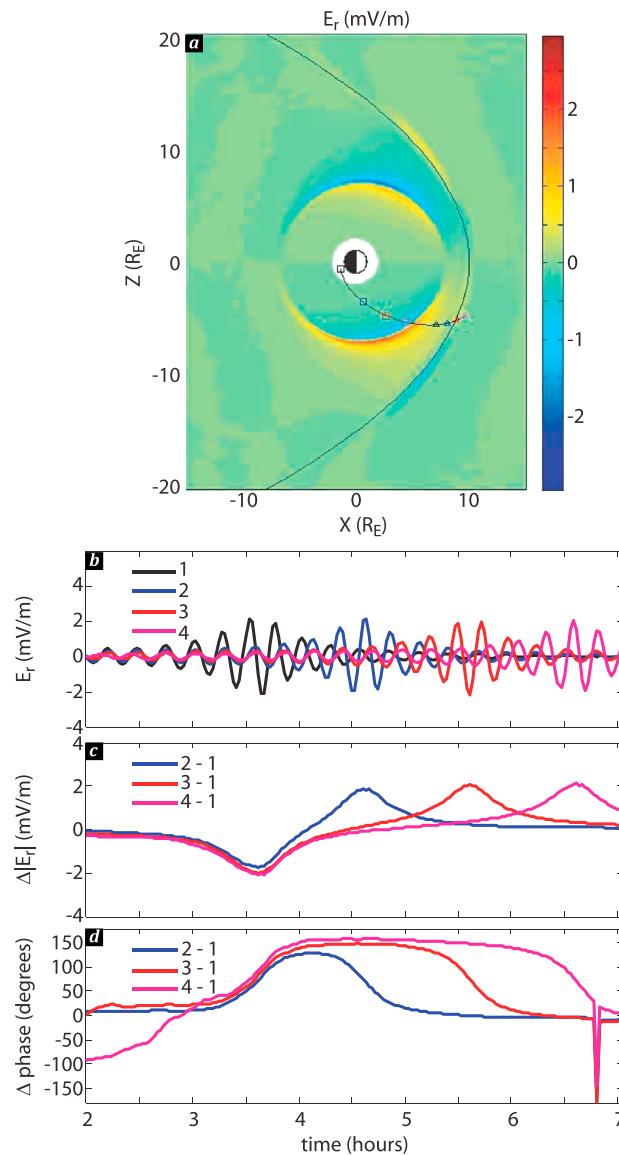
this FLR in the magnetotail using the combined THEMIS and GOES satellite constellation. Figure 7 shows magnetic field perturbations recorded from THEMIS and GOES satellites, transformed into field-aligned coordinates, where  $Z$  is field aligned,  $Y$  is azimuthal, and  $X$  makes up the right-handed set, which in the equatorial plane is directed outward in the direction of  $R$ . A background field determination of 200 s was applied.

Figure 7 shows that there are two distinct periods of ULF wave activity during the 0700–0800 UT period, most notably in THEMIS A, D, E, and GOES 12. First, between 0715 and 0725 UT, a substorm-like disturbance is seen both on the ground and in space. Subsequently, between 0745 and 0800 UT and most notably in THEMIS A, D, E, and GOES 12, ULF waves were observed to begin following a second substorm at around  $\sim 0742$  UT and persisted for the remainder of the interval. Periodic ULF waves at lower frequencies to those observed in the aurora ( $\sim 7$  mHz) were observed at GOES 12 in the azimuthal magnetic field component ( $B_y$ ) and in the compressional components ( $B_z$ ) in both GOES 11 and 12. We interpret these waves as the formation and evolution of the substorm current wedge at geosynchronous orbits via bouncing Alfvén waves [e.g., Southwood

and Hughes, 1985; Olson, 1999]. However, it is important to note that in the period 0730–0740 UT, during the clearest signatures of the auroral FLR, there is no sign of the 8 mHz magnetic perturbations one would expect to find during a poloidal-mode FLR nor is there any signature of modulated electron signatures at any THEMIS satellite that would correspond to the periodic precipitation signature seen in the aurora (not shown).

The magnetotail magnetic field distortions may complicate the eigenstructure of the mode, and there is no guarantee that the FLR is a fundamental field-aligned harmonic; hence, the FLR might be seen in the electric rather than the magnetic field, depending on field-aligned harmonic mode and distance from the nodes (see the discussion in Ozeke *et al.* [2009]). Figure 8 shows the electric fields observed by THEMIS in the same field-aligned coordinate system. In this coordinate system, it is important not to compute the third component of electric field using the  $E \cdot B = 0$  approximation when the electric field vector is within  $\pm 15^\circ$  of the spin plane, and as a precautionary measure, we also do not compute electric fields during the rapidly varying magnetic fields during the substorm expansion phases. Again, during the key 0730–0740 UT period preceding substorm onset, there is no ULF wave activity observed at any of these satellites in either the electric or magnetic fields observed at THEMIS. The question then becomes, where is the magnetospheric energy source for the FLR which seems to be so unmistakably like a high- $m$  FLR as seen in the ground-based observations?

The answer is unclear and especially surprising even given the excellent satellite coverage during this event. Certainly, no THEMIS or GOES satellite appears to be close to the magnetospheric counterpart of the FLR, since no satellite observes any electromagnetic signature of a wave at this frequency. However, this statement has more fundamental importance for the substorm onset mechanism in this case: if a FLR is observed precisely at the location of substorm onset, but none of the extensive satellite fleet is in the “correct” location



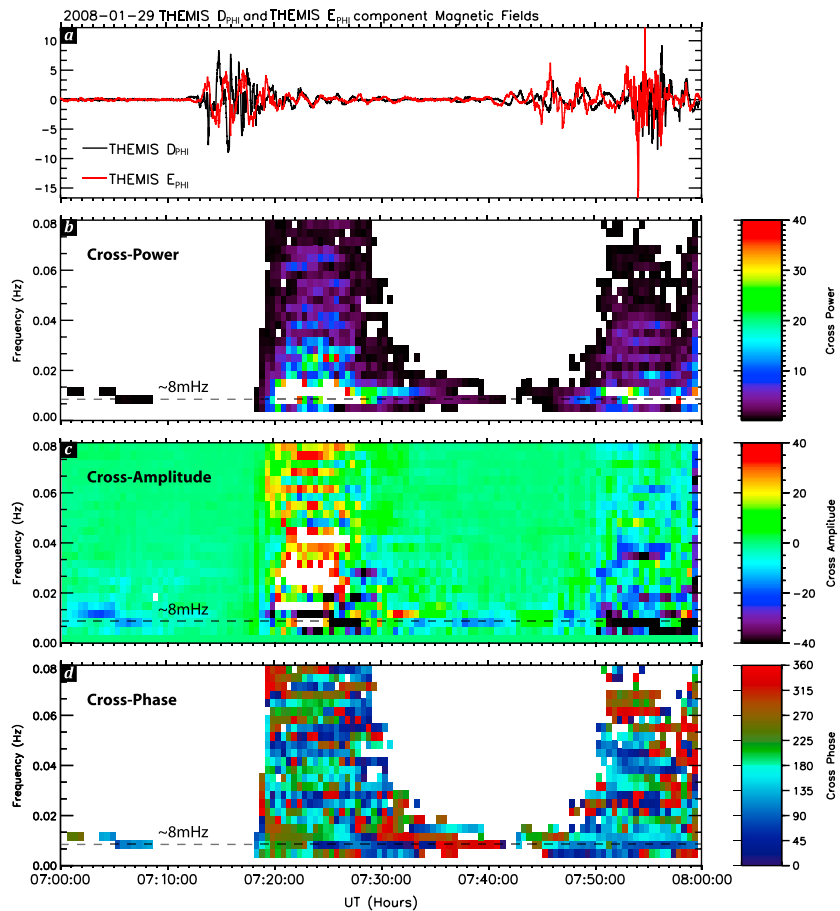
**Figure 9.** (a) A snapshot of the radial electric fields taken from the ULF wave model outlined by *Degeling et al.* [2011, 2013] of a 1 mHz driven field line resonance. Overplotted in Figure 9a are four sample THEMIS-like orbits at 1 h intervals where the triangles mark the beginning of each satellite trajectory ( $t = 2$  h), and the squares mark the end ( $t = 7$  h). (b) The simulated time series recorded by each satellite as a function of time, (c) the amplitude difference seen between each satellite pair, and (d) the cross phase between each satellite pair to aid the interpretation of Figure 10.

of sample THEMIS satellite orbits through an idealized driven FLR [from *Degeling et al.*, 2011, 2013] for reference and interpretation of the in situ satellite results shown below. All virtual satellites in the simulation observe the amplitude peak and  $180^\circ$  phase change in the same location but at different times due to their respective orbital locations. This means that the traditional cross-power peak and  $180^\circ$  phase change do not form bands of constant phase as a function of time; rather, as the satellite moves in location, a cross-amplitude maxima then minima (or cross-power peak with a reduction in power at the middle) can be seen across a region of changing phase that first displays a  $180^\circ$  phase change before returning to an original phase value.

to observe the FLR in the magnetosphere, then can we really trust the ground mapping of satellites in the magnetotail? Of course, magnetic mapping using statistical models such as Tsyganenko is expected to be at their worst at times of temporally limited extreme field distortion such as immediately preceding substorm onset—such that it is possible that the field lines connecting to the auroral FLR do not map to any of these satellite locations. We note that at geosynchronous altitudes, the T96 model slightly underpredicts the observed magnetic field strength, whereas at THEMIS A, D, and E distances, the T96 model overpredicts the observed magnetic field strength. We discuss the ramifications of this in section 6.

To combat this, we turn to the cross-phase technique [e.g., *Waters et al.*, 1991a, 1991b], which is generally used to determine the fundamental resonant eigenfrequency of a field line that lies at the midpoint of two latitudinally separated ground-based magnetometers. It is also generally assumed not to work in the nightside magnetosphere/ionosphere due to reduced ionospheric conductivity. However, in selected case studies [e.g., *Rae et al.*, 2007c] it has been shown that the cross-phase technique can render discrete points of the Alfvén continuum during substorms. In this case study, we apply the cross-phase technique to the THEMIS FGM measurements in order to directly measure the field line eigenfrequency at the midpoint of the two THEMIS probes.

For spacecraft measurements, the cross-phase technique works in the same way to define a field line eigenfrequency at a particular L shell. By their very nature, however, satellite measurements are taken crossing L shells, which adds a subtle twist to the interpretation of cross-phase results. Figure 9 shows an example



**Figure 10.** (a) The azimuthal component perturbations from THEMIS D and E from 0700 to 0800 UT as shown in Figure 7 together with their (b) cross-power spectrum, (c) cross-amplitude spectrum, and (d) cross-phase spectrum. The horizontal dashed line denotes the 12 mHz FLR frequency as observed by the FSIM ASI for reference.

Figure 10 shows cross-phase analysis from the THEMIS D and E satellites for the period encompassing the FLR and subsequent expansion phase onset from 0700 to 0800 UT. Figures 10a–10d show time series for the azimuthal component of the magnetic field, the cross-power, cross-amplitude, and cross-phase spectra. Two discrete tail activations are encompassed by this interval, which can be seen around ~0712 UT and after 0740 UT. In between, very little magnetic activity is seen, though small magnetic field perturbations can be seen in both THEMIS D and E time series. A peak in cross power is seen following the first activation in the ~6–13 mHz frequency range, and a suggestive reduction of cross power is seen in the 6–10 mHz band (c.f., Figure 9). Further, the cross amplitudes at these frequencies display a maximum to minimum reversal, while a 180° phase change is recorded between the satellites. We therefore conclude that the resonant fundamental eigenfrequency of the field lines that thread the THEMIS D and E satellite locations is 6–10 mHz. Therefore, we can conclude that the field line that maps to the onset location must be close to, but inside of, the radial distances of 11.65 and 11.8  $R_E$  of THEMIS D and E, respectively.

## 6. Discussion

Field Line Resonances have been observed in the nightside magnetosphere both during quiet times [e.g., Hughes and Gard, 1984; Takahashi et al., 1996; Kim et al., 2001] and in close conjunction with substorms [e.g., Takahashi et al., 1988; Nose et al., 1998; Keiling et al., 2003; Rae et al., 2007c]. Takahashi et al. [1988] showed the first unambiguous evidence of substorm-associated standing Alfvén waves in the nightside magnetosphere. Keiling et al. [2003] discovered a number of toroidal mode FLRs during substorm-like magnetic bays using the Polar satellite and ground-based measurements. These authors found that the FLRs in the Pi2 period range occurred over a wide range of MLTs from 22 to 06 MLT and L shells that range from 4 to 7. Rae et al. [2007c]

demonstrated that auroral zone Pi2 pulsations following substorm onset could be described as an FLR by identifying that the frequency of the Pi2 pulsation corresponded to the expected toroidal mode field line eigenfrequency within the Alfvén continuum. Substorms and FLRs were first postulated to be related to each other by *Samson et al.* [1992a, 1996], both as a trigger for the explosive energy release and also to serve as a marker for the locale of substorm initiation in the magnetosphere. The FLRs reported in the substorm work of *Samson et al.* [1992b, 1996] generally tended to be of lower frequencies than Pi2 frequencies (1–4 mHz FLR frequencies and c.f. 6–25 mHz Pi2 frequency range). However, it is possible that Pi2s might exhibit resonant behavior, as *Rae et al.* [2007c] showed, or might be part of a continuum of wave power that is enhanced during a substorm, as *Rae et al.* [2011] demonstrated.

We summarize the pioneering work of Samson et al. and place our results in context:

1. *Samson et al.* [1992b] presented evidence from Super Dual Auroral Radar Network (SuperDARN) radar and ground magnetometers of FLRs observed in a 2–3 h interval that encompassed a substorm onset (see their Figures 7 and 8 for example). This important work suggests the presence of FLRs with large enough scale to be observed clearly by ground-based magnetometers. We present an FLR that has significantly smaller scale and is therefore only seen clearly in an auroral imager.
2. *Samson et al.* [1996] presented a case study whereby FLRs were observed close to pronounced auroral brightenings in the nightside in the premidnight sector. Samson et al. suggested that the events studied were not intense enough to be substorms [*Samson et al.*, 1996, p. 17,378], although we note here that the aurora did intensify and a magnetic bay was observed which would be considered an auroral substorm in the recent literature. We present a more active event that has all the characteristics of a substorm [*Lui et al.*, 2008; *Mende et al.*, 2009; *Nishimura et al.*, 2010; this paper]. We use the high spatial resolution THEMIS ASIs in order to determine the scale size and phase propagation of the auroral FLR signature, and thereby test Samson et al.'s hypotheses prior to a documented substorm.
3. We augment the ground-based observations with space-based data sets that constrain the location of the growth phase FLR and hence substorm onset. It has not been possible to do this before. The fortuitous conjunction of the THEMIS probes provides critical new evidence as to where the growth phase arc maps to.
4. *Samson et al.* [1992a] demonstrated that toroidal FLRs (poleward phase propagation) could play a role in substorm onset. Here we show that a mode with smaller azimuthal scales can also play a role in substorm onset, which may point to a particle generation mechanism, or certainly an internally generated FLR source.

The optical signature of this FLR reduced in intensity just before onset in the same way as other auroral forms have often been seen to dim immediately before substorm onset [e.g., *Pellinen and Heikkila*, 1978]. Further, recent observations have shown that substorm onsets may be preceded by a localized reduction of FAC density and M-I coupling [*Murphy et al.*, 2012, 2013]. The observations presented here indicate that the FAC density reduction may be mediated by standing shear Alfvén waves, perhaps due to the depletion of current carriers [*Damiano and Wright*, 2008].

We sought to find the magnetospheric counterpart of the ionospheric signature of this FLR during a major THEMIS conjunction to which we added the magnetic field measurements available from the GOES satellites. The THEMIS major conjunction is not perfectly aligned in MLT with the onset location but with the augmentation of the GOES constellation, eight satellites are in favorable locations, and we expected to observe the FLR in space based on statistical magnetic field mapping through the Tsyganenko models. No such periodic, long-lasting wave activity is observed in the electric and magnetic fields at any of the satellite locations in the interval during which the aurora demonstrates clear periodic behavior. This null result has fundamental implications for the mapping of the onset region in space. The FLR observed on the ground is collocated with the onset region in the ionosphere to within instrumental resolution. Given the lack of an observable magnetospheric counterpart, then assuming that the ionospheric FLR does indeed correspond to a conjugate magnetospheric FLR, the combined satellite constellation determines all of the locations in the magnetosphere where the onset region cannot be. Figure 1 shows the locations of the satellites and indicates that the onset region in space cannot be around geosynchronous orbit nor can the onset region be in the 8–10  $R_E$  region around midnight. Presumably, then, the meridian of onset lies to the west of the THEMIS major conjunction, and at distances further than 6.6  $R_E$  from the Earth. However, with the addition of space-based cross-phase measurements of the local field line eigenfrequency, we do not need to rely on what is inherently unreliable magnetic field mapping during the growth phase. The optical FLR has a period of 85 s, corresponding to

eigenfrequencies of around 12 mHz. Using a dipole approximation for the magnetic field and with a 1 amu/cc density estimate derived from 0.5 to 1 particles/cc measured by THEMIS ElectroStatic Analyzer (ESA) [McFadden *et al.*, 2008], we estimate that this eigenfrequency corresponds to L shells outside geosynchronous for a high-*m* mode FLR. Using cross-phase measurements of the local field line eigenfrequency at THEMIS D and E, we find that the local field line eigenfrequency is 6–10 mHz. Hence, we can reliably say that this 12 mHz FLR must lie inside of THEMIS locations. The only reasonable way that the eigenfrequency could increase as a function of distance from the Earth is due to large changes in number density, e.g., due to the plasmopause. It is unlikely that the plasmopause would be located between 6.6 and 11  $R_E$  in the magnetotail, and so we conclude that the 12 mHz FLR must therefore map to a location that is radially closer to the Earth than the THEMIS D and E satellites but closer to the Earth. In summary, it is most likely that the onset region for this substorm was located in regions west of the THEMIS meridian and between 6.6 and 11  $R_E$  radial distance.

Unfortunately, the available satellite conjunctions are in locations such that the magnetospheric source of this FLR was not observed. While this is puzzling, it could be explained by the uncertainties in magnetic field line mapping models between the ionosphere and magnetosphere—and whose errors are expected to be especially large during these times of stretched fields immediately prior to substorm onset. For example, Shevchenko *et al.* [2010] showed that the average difference between mapping the ion and electron isotropy boundaries in the magnetotail to the ionosphere using three established magnetic field models resulted in a 2° latitudinal difference, which increased significantly away from midnight, which is certainly applicable in this case. However, this demonstrates that even using the powerful observational configurations associated with a major THEMIS conjunction does not guarantee that one will be observing the onset region with the available in situ satellite coverage. Here we reiterate that care must be taken with inferred magnetic mappings and inferred connections between, for example, ionospheric substorm onsets and specific in situ locations in the magnetosphere. This is further exacerbated by the possibility that the onset region in the magnetosphere may be small. If an extended (~1 h of MLT) nightside auroral onset signature is not observed by a major THEMIS conjunction, augmented by three GOES satellites, as in this case then it suggests that even more care must be taken when drawing conclusions from combined auroral and magnetospheric observations. This is especially important in relation to attempts to identify the causality of magnetospheric processes in triggering substorm onset. Externally driven FLRs have been shown to produce auroral precipitation [e.g., Rankin *et al.*, 2005; Rae *et al.*, 2007b], but in these cases optical emissions show poleward phase propagation [e.g., Wright and Allan, 1996; Milan *et al.*, 2001]. In contrast to this, high-*m* FLRs are expected to demonstrate equatorward phase propagation due to their internal energy source [e.g., Mann, 1998]. Internal energy sources include a “bump-on-tail” unstable ring current ion particle distributions [e.g., Southwood *et al.*, 1969; Wright *et al.*, 2001], a pressure gradient [e.g. Southwood and Hughes, 1983], or a number of other mechanisms that can extract free energy from plasma, like the drift mirror instability [e.g., Hasegawa, 1969; Rae *et al.*, 2007d], the ballooning instability [e.g., Chan *et al.*, 1994], or a combination of both [e.g., Chen and Hasegawa, 1991]. In short, we leave the source of the plasma instability responsible for this FLR to future study. However, the search for the source of substorm onset in the magnetosphere and the magnetospheric counterpart of this FLR must, in our opinion, occur in tandem.

ULF waves have long been known as a repeatable substorm feature at, or immediately following, substorm onset [e.g., Bösinger *et al.*, 1981; Olson, 1999]. These waves were first thought to be either localized to the longitude of substorm onset in the case of short-period Pi1B waves [e.g., Bösinger *et al.*, 1981; Posch *et al.*, 2007] or be observed globally throughout the nightside ionosphere in the case of Pi2 wave band [e.g., Olson, 1999]. More recently, ULF wave amplitudes across a period range spanning the Pi1 and Pi2 ULF wave bands were found to provide a repeatable marker of the location in time and space of substorm onset, revealing the existence of a magnetic “epicenter” to substorm onset that accompanies the better known optical signature [e.g., Milling *et al.*, 2008; Murphy *et al.*, 2009a, 2009b; Rae *et al.*, 2009a, 2009b, 2010, 2011, 2012]. However, there is very little literature describing the presence or characteristics of wave activity prior to substorm onset, since on average the magnetic ULF wave power is ~2 orders of magnitude lower prior to auroral substorm onset than it is afterward [e.g., Murphy *et al.*, 2011; Rae *et al.*, 2011]. However, in this case study, we show that ULF wave activity in the auroral display unambiguously exists for 15 min immediately prior to substorm onset, and on the onset arc, and appears to be either disrupted or destroyed by substorm onset. The relatively short azimuthal wavelengths (i.e., high-*m* numbers) of the wave activity are such that ground magnetometers cannot detect the ground-based magnetic counterpart of the waves well due to the Biot-Savart

integration of all overhead current systems. The only exception to this is for giant pulsations, where the spatial attenuation is more than compensated for by their very large amplitudes [e.g., *Wright et al.*, 2001] and ground-based magnetometer observations can detect their presence even for middle-*m* to high-*m*. This study uses the auroral intensity measurements instead of the more traditional magnetometer observations to reveal the FLR characteristics. High-*m* waves can also be seen with ionospheric radar such as SuperDARN [e.g., *Fenrich et al.*, 1995]. It is certainly possible that the characteristics of ULF waves change during onset. That is, high-*m* ULF waves could occur prior to onset and evolve into larger spatial scale structures following onset, in the manner that *Rae et al.* [2009, 2010] describe, whereby the first signatures of substorm onset are observed to possess smaller spatial scale periodic azimuthal auroral forms, before developing into larger-scale auroral undulations that subsequently roll into vortices and breakup. Therefore, the findings presented within this paper are consistent with the traditional viewpoint that ground-based magnetometer measurements of ULF wave amplitudes increase significantly at substorm onset, but we postulate that the wave characteristics as well as their amplitudes change following onset.

From the combined measurements of THEMIS in situ and ground-based auroral measurements, we can see that the 0700–0800 UT period encompasses two substorm onsets that sandwich a period of field line resonance. It is likely that the first auroral breakup gave rise to a broadband ULF spectra in the Pi1–Pi2 frequency range [e.g., *Rae et al.*, 2011], and once the recovery phase has taken place, all that remains is wave energy at the single frequency of the FLR, or free particle energy in order to drive the FLR [e.g., *Wright et al.*, 2001; *Baddeley et al.*, 2005]. Following another substorm that is either coincidentally or causally linked to this FLR, another broadband ULF spectra is launched, and the resulting breakup destroys the coherent signature of the FLR once more.

Of primary concern to the interpretation of this data set is the relationship between the auroral signature of the FLR and substorm expansion phase onset. The observations show the presence of a periodic repeating signature of auroral arc generation remarkably close to the initiation region of the substorm. Recent work has led to the suggestion that equatorward moving auroral features are a trigger for substorms [e.g., *Nishimura et al.*, 2010]. In essence, bursts of reconnection-driven fast flows are injected into the near-Earth magnetotail region, such that the earthward transport of new plasma leads to a near-Earth instability some ~5–10 min later. In this modified “outside-to-in” onset framework, Nishimura and coworkers propose that an equatorward moving auroral feature represents a fast earthward flow from a reconnection source downtail that primes the inner magnetosphere for onset in close conjunction with the Harang discontinuity [e.g., *Heppner and Maynard*, 1987]. The equatorward moving auroral form, initiated at the poleward boundary in the form of a PBI, eventually comes into close (ionospheric) conjunction with the onset arc, which then brightens and expands poleward. In a series of papers [e.g., *Nishimura et al.*, 2010] these authors have used observations from multiple PBI-related onset events to suggest that a PBI should be observed on the order of 5 min (on average) prior to the visual determination of substorm onset. For the event interval presented here, which has been identified by Nishimura et al. as a PBI-related onset event, a faint auroral feature is identified at 0738 UT in the northeast sector of the FSMI field of view (Figures 2g and 5f) as the onset-causing PBI. We show two observations that significantly challenge this hypothesis.

First, we show that the auroral form denoted as a PBI by Nishimura et al. does not progress significantly equatorward during this interval and so is in fact unlikely to be involved in the onset process (see supporting information and the auroral form highlighted by arrows in Figures 2f and 5f). Since this interval is listed in the *Nishimura et al.* [2010] PBI onset list and is indicated in that list to represent an especially strong candidate interval for the PBI-related onset model, we believe that it is important to emphasize this point here. Perhaps more importantly, this PBI still exists after substorm expansion phase onset has begun significantly westward and equatorward of this location, before being enveloped in the substorm expansion phase some ~2 min later.

In this case study, we demonstrate instead that a small-scale (or high-*m*) FLR is operating immediately preceding, and in the same spatial location, as substorm onset. The characteristics of this FLR changed during substorm onset, which indicates that at the very least the FLR is affected by the onset process, whereas the PBI appears to be unchanged. This FLR that was first observed some 15–20 min prior to substorm onset is the onset arc that breaks up and precedes the PBI defined in the *Nishimura et al.* [2010] defined onset list by 10–15 min.



This begs the fundamental question as to which auroral diagnostic, if either, is actually causally related to substorm onset. We therefore state what we regard are all of the different possibilities relating to the causality between these two auroral features, namely, the FLR and the PBI, and the triggering of substorm onset.

1. Under different conditions, either a PBI or a FLR may be the direct sign of the process that triggers substorm onset;
2. Both PBIs and FLRs may signify part of the substorm onset sequence, such that onset is triggered by some other physical process that is itself caused by the flows associated with PBIs or the instability that causes the FLR; and
3. The occurrence of PBIs and FLRs is simply statistical, such that they are unrelated to onset but at times their occurrence may both be coincidental with the time of onset purely by chance.

Since the FLR is affected by the onset process, whereas the PBI signature occurs in a different spatial location and is unchanged by the onset process, it seems clear that this event may be more related to the physics of field line resonance as opposed to a PBI-triggered onset. Undeniably, the energy of the FLR is significantly larger than any PBI, by over a factor of 2, as given by the intensities of the respective auroral features. Whether an FLR is a necessary condition for triggering substorm onset cannot be concluded without quantified statistical studies. On the other hand, this also means that no other proposed physical mechanism can be concluded to be responsible for this onset either [e.g., *Lui et al.*, 2008; *Mende et al.*, 2009; *Nishimura et al.*, 2010], since none of these studies can explain the existence of the FLR.

Finally, it is interesting to note that PBIs are now an evolving term in the literature. Traditionally, PBIs were known to be intensifications at the poleward boundary of the auroral oval and a recovery phase phenomena [e.g., *Lyons et al.*, 1999]. From this location, a primarily north-south aligned auroral finger or streamer often (but not always) evolves equatorward [e.g., *Liu et al.*, 1995; *Henderson et al.*, 1998]. Recently, the term PBI has evolved to include the auroral streamer that initiates poleward of the presumed poleward boundary and appears to progress equatorward from this location in any orientation, north-south or east-west, or indeed a combination of both [e.g., *Nishimura et al.*, 2010]. What the original and revised definitions have in common is that auroral forms evolve equatorward from a poleward location. Interestingly enough, we show that another auroral form can also possess the same criteria as the revised PBI definition used in the literature—the high- $m$  field line resonance. We show clearly that the high- $m$  FLR in this case study has equatorward phase propagation, characteristic of the revised definition of a PBI used recently in the literature. It is therefore possible that repeating “poleward boundary intensifications” prior to substorm onset may be in some cases the misidentified optical signature of a field line resonance with a localized energy source.

## 7. Conclusions

In this paper we investigate a substorm that has been the subject of three previous papers and show that considerations of the onset process must include the physics of a small azimuthal scale, or high- $m$ , field line resonance. Selected data during this event have been interpreted as current disruption [*Lui et al.*, 2008] or reconnection driven [*Nishimura et al.*, 2010], and the evolution of magnetotail dynamics during this event cannot be reproduced by time-of-flight calculations [*Mende et al.*, 2009]. The data presented in this paper show that in addition to the aspects picked out by these previous authors, there is a clear and unambiguous signature of an FLR operating at the location of substorm onset in the ionosphere that has been omitted from previous investigations of this event. This case study reveals that a high- $m$  FLR was in effect at the precise location of substorm expansion phase onset and over the interval encompassing before and after the onset, with different characteristics following onset. *Samson et al.* [1992b] found that large azimuthal scale, or low- $m$ , FLRs were observed during intervals that included a substorm. *Samson et al.* [1996] presented a case study whereby low- $m$  FLRs were observed during the growth phase of a substorm. In this paper we concentrate exclusively on the role of FLRs during the growth phase to tie this auroral observation of an FLR to the onset process directly. We show that a small azimuthal scale FLR is observed prior to, and in the immediate vicinity of, substorm onset. Whether the results of *Samson et al.* [1992a, 1996] and this paper demonstrate different elements of the same phenomenon, for example, that the high- $m$  FLR develops into a low- $m$  FLR via dispersive effects along the geomagnetic field [e.g., *Lu et al.*, 2003, 2007; *Rankin et al.*, 2005] remains to be determined. However, the FLR-driven substorm as first suggested by *Samson et al.* [1992a, 1996] still remains as viable a candidate trigger mechanism for substorm onset as any existing substorm paradigm.

We further show the utility of ULF waves to determine preonset field line topology, providing evidence that the FLR signature originates closer to the Earth than the inner magnetospheric THEMIS probes. For this event, during a major THEMIS conjunction, we were unable to find any electromagnetic field signature of the FLR in space—even when our analysis was augmented by observations from three geosynchronous GOES satellites (providing an eight-satellite conjunction). Using the first space-based cross-phase analysis of field line eigenfrequencies in the nightside magnetosphere, we are able to constrain the magnetospheric FLR location to be between geosynchronous orbit and  $11 R_E$ .

We also show conclusive evidence that equatorward moving auroral forms do not have to be PBI/streamers, which is timely in the current literature since several authors have appealed to PBI-triggered substorms by identifying equatorward moving auroral forms progressing close to the region of substorm onset in the manner that *Nishimura et al.* [2010] proposed.

Our study highlights that observations of substorm growth phase are important, since the FLR signature during this event starts tens of minutes before auroral onset and persists all the way through the interval. Future studies where FLRs are observed could be used to further constrain not only the onset location but also the potential causal role of FLRs in the onset process.

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