



## Correlation of substorm injections, auroral modulations, and ground Pi2

A. Keiling,<sup>1</sup> V. Angelopoulos,<sup>1</sup> D. Larson,<sup>1</sup> R. Lin,<sup>1</sup> J. McFadden,<sup>1</sup> C. Carlson,<sup>1</sup> J. W. Bonnell,<sup>1</sup> F. S. Mozer,<sup>1</sup> K.-H. Glassmeier,<sup>2</sup> H. U. Auster,<sup>2</sup> W. Magnes,<sup>3</sup> S. Mende,<sup>1</sup> H. Frey,<sup>1</sup> A. Roux,<sup>4</sup> O. LeContel,<sup>4</sup> S. Frey,<sup>1</sup> T. Phan,<sup>1</sup> E. Donovan,<sup>5</sup> C. T. Russell,<sup>6</sup> I. Mann,<sup>7</sup> W. Liu,<sup>8</sup> X. Li,<sup>8</sup> M. Fillingim,<sup>1</sup> G. Parks,<sup>1</sup> K. Shiokawa,<sup>9</sup> and J. Raeder<sup>10</sup>

Received 12 March 2008; accepted 4 April 2008; published 6 June 2008.

[1] In this case study we report a substorm, 23 March 2007, which exhibited oscillations with a period of  $\sim 135$  s in three substorm phenomena all of which were one-to-one correlated. The in-situ observations are from one THEMIS spacecraft (8.3  $R_E$  geocentric distance) and the geosynchronous LANL-97A spacecraft. The focus here is on the intensification phase during which THEMIS was conjugate to the region of auroral brightening and its foot point was near the high-latitude ground station Kiana. The following results will be demonstrated: (1) THEMIS and LANL-97A (time-delayed) recorded periodic ion injections ( $>100$  keV). (2) Near-conjugate high-latitude ground magnetometer data show very large Pi2 ( $\delta H \sim 150$  nT) with a 6-s time delay compared to the THEMIS ion injections. (3) Low-latitude ground magnetometer data also show Pi2 with the same waveform as the high-latitude Pi2 but with longer time delays (20–31 s). (4) Auroral luminosity was periodically modulated during the intensification phase. (5) All three signatures (ion injections, ground Pi2, optical modulation) had the same periodicity of  $\sim 135$  s but with various time delays with respect to the THEMIS ion injections. These observations demonstrate that the three substorm phenomena had a common source which controlled the periodicity. **Citation:** Keiling, A., et al. (2008), Correlation of substorm injections, auroral modulations, and ground Pi2, *Geophys. Res. Lett.*, 35, L17S22, doi:10.1029/2008GL033969.

### 1. Introduction

[2] Auroral breakup, substorm injections in the near-Earth plasma sheet and ground Pi2 pulsations are phenom-

ena associated with substorms and are the result of various physical processes. A complete understanding of how they are interrelated is still outstanding. Various studies have investigated relationships in combinations of two of these signatures. For example, *Yeoman et al.* [1994] demonstrated that the detection of injected particles at geosynchronous orbit and Pi2 pulsations on the ground are highly correlated. *Liou et al.* [2000] reported that low-latitude Pi2s are subject to delays of 1–3 min in comparison to auroral breakups and this delay depended on the relative location to the breakup region. *Liou et al.* [2001] compared the onset of dispersionless particle injections at geosynchronous orbit with the start of auroral breakups and found a lag time of  $-2$  to 8 min.

[3] These reported correlations refer to the near-simultaneous occurrence of the various phenomena which are now well documented. They do not, however, refer to one-to-one correlations of any periodic behavior as found in Pi2 pulsations. In this study we report an event which shows periodic oscillations in all three substorm phenomena which were one-to-one correlated.

### 2. Observations

[4] On 23 March 2007 a substorm occurred while the THEMIS fleet [*Angelopoulos*, 2008] was located in the pre-midnight region at 8 to 13  $R_E$  geocentric distances. Ground data (optical and magnetic field) recorded the substorm onset and a subsequent intensification (Figure 1). The focus in this paper is on analyzing the magnetic field oscillations and particle injections recorded by spacecraft TH-C ( $-6.2 R_E$ ,  $5.5 R_E$ ,  $-0.6 R_E$  in GSM coordinates at 11:20 UT) that were associated with the substorm intensification in comparison to the ground signatures. In addition, we utilize data from the LANL-97A and Polar satellites. The Polar-UVI imager recorded an abrupt auroral brightening (i.e., intensification) west of the initial onset region (Figures 1a and 1b; also see Figure 3d). Magnetometer data at Kiana station (KIAN) show a very large drop in the  $H$  component ( $\sim 150$  nT), followed by additional large-amplitude oscillations with peak-to-peak perturbation of 50–100 nT and with Pi2 period (Figure 1f). At the same time, TH-C recorded an ion injections with very high energies ( $>100$  keV; Figure 1c). Although periodic ion enhancements can be seen before the intensification, they are limited to lower energetic ions. These pre-intensification oscillations coincide with much smaller Pi2 pulsations at KIAN. Furthermore, strong ion upflow (Figure 1d) occurred on the same field lines as those carrying the energetic ion injections, suggesting that TH-C was on active auroral field

<sup>1</sup>Space Sciences Laboratory, University of California, Berkeley, California, USA.

<sup>2</sup>Institut für Geophysik und Extraterrestrische Physik, Technische Universität Braunschweig, Braunschweig, Germany.

<sup>3</sup>Space Research Institute, Austrian Academy of Science, Graz, Austria.

<sup>4</sup>CETP, IPSL, Velizy, France.

<sup>5</sup>Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada.

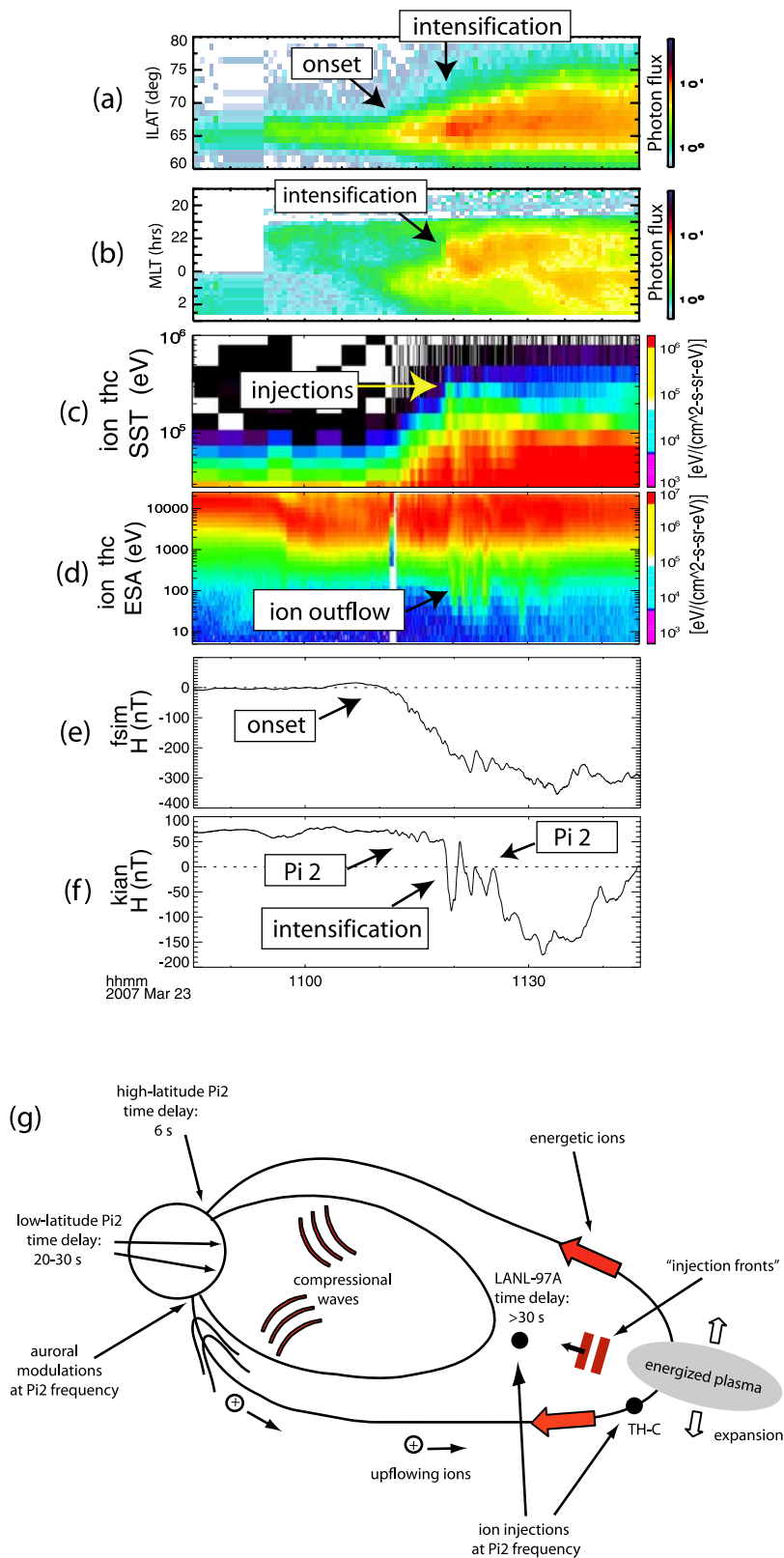
<sup>6</sup>IGPP, ESS, University of California, Los Angeles, California, USA.

<sup>7</sup>Department of Physics, University of Alberta, Edmonton, Alberta, Canada.

<sup>8</sup>LASP, University of Colorado, Boulder, Colorado, USA.

<sup>9</sup>Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Japan.

<sup>10</sup>Space Science Center, University of New Hampshire, Durham, New Hampshire, USA.



**Figure 1.** Overview of the 23 March 2007 substorm. (a, b) Keograms from Polar-UVI; (c, d) ion energy-time spectrograms from SST (D. Larson et al., manuscript in preparation, 2008) and ESA (J. P. McFadden et al., THEMIS ESA first science results and performance issues, submitted to *Space Science Reviews*, 2008); (e, f) magnetometer data from Fort Simpson ( $61.8^\circ$  latitude,  $238.8^\circ$  longitude geographic) and Kiana ( $66.97^\circ$  latitude,  $199.56^\circ$  longitude geographic) (C. T. Russell et al., THEMIS ground-based magnetometers, submitted to *Space Science Reviews*, 2008); and (g) schematic illustration summarizing the observations and some speculated phenomena reported in this study.

lines. The schematic illustration in Figure 1g combines the various observations and some speculated phenomena which will be described next.

[5] Figure 2 shows an expanded view approximately centered on the onset time of the auroral substorm intensification ( $\sim 11:19$  UT). This onset coincided with a near-dispersionless ion injection (Figures 2b and 2e), followed by two more near-dispersionless ion enhancements/injections in the highest energy channels ( $>100$  keV and  $<500$  keV; lower three lines and arrows in Figure 2e). The three injections have a period of about 135 s which can also be seen in Figure 2k where only one energy channel (230–327 keV) is shown. In contrast, the lower energetic ions ( $<100$  keV; Figures 2f and 2g; note the linear scale in Figure 2f) show flux enhancements that are different. For example, there are periodic flux enhancements in the lower energy channels before the intensification (11:12–11:16 UT) and during the time period of the three energetic ion injections (11:19–11:25 UT) which are not seen in the highest energy channels. These differences show that the energization of the substorm injections was energy dependent.

[6] Moreover, Figures 2f–2h reveal that the field-aligned magnetic field component,  $B_z$ , and the flux enhancements of the lower energy ions ( $<89$  keV) were out of phase by  $180^\circ$  (dashed lines). This diamagnetic relation is indicative of plasma sheet motion that allows the spacecraft to probe the inhomogeneous plasma environment. In addition, a spacecraft entering (leaving) a boundary layer will record dispersion (reversed dispersion) in pitch angle with  $90^\circ$ -particles arriving first and  $0^\circ$ -particles later. This can be seen in Figure 2d showing azimuth-time spectrograms for all SST energies (note that the z scale is adjusted for the time interval encompassing the main ion injections). Considering the magnetic field and particle sensor orientation, it turns out that the azimuth is a good approximation of pitch angle during this particular time interval with azimuth angles of  $130^\circ$  and  $310^\circ$  (solid and dashed white lines) approximately corresponding to the field-aligned ( $0^\circ$  pitch angle) and anti-field-aligned ( $180^\circ$  pitch angle) directions [Angelopoulos *et al.*, 2008]. The dispersions - some of which are marked with white arrows - line up with depressions and enhancements of the total magnetic field in accordance with the boundary motion interpretation (see also Angelopoulos *et al.*, 2008, who applied the remote sensing technique to ions with energies  $>40$  keV, occurring during the intensification onset, and found that the energetic ions were horizontally layered and expanded southward, i.e., lobeward, at speeds of 70–80 km/s). Minimum variance analysis applied to the magnetic field during the first energetic ion injection boundary (11:19–11:22 UT) (not shown here) yields mostly a north-south normal direction and an angle of about  $74^\circ$  between normal and total magnetic field which is also

consistent with the boundary motion direction as inferred from the particles.

[7] It is also noted that the pitch angle fine structure visible in Figure 2d in the time interval between the first and the third main injections (11:19–11:25 UT) temporally matches the occurrences of upflowing ions (Figure 2c). This correspondence might be due to the periodic entering and leaving of the boundary which carries continuously upflowing ions. Such upflowing ions generally exist on active auroral field lines. Below we will argue that TH-C was indeed conjugate to auroral brightening, i.e., active auroral field lines. The first delayed ion upflow ( $\sim 11:20$  UT), on the other hand, might be a travel time effect of the first low-altitude ions that are accelerated at intensification onset and are flowing up the field lines to the location of TH-C.

[8] Returning to the most energetic ion injections, Figure 2a shows that they also show pitch angle (azimuth) dispersion, but with much less fine structure compared to the lower energetic particles. This difference suggests an expanding motion of the associated hot plasma independent of the lower energetic particles. We also noted (above) that there was no significant energy dispersion in the energy flux of different energy channels ( $>100$  keV). This is in contrast to the observations of LANL-97A which was located closer to Earth. The geosynchronous satellite (see footprint mapping in Figure 3) recorded energetic ion injections associated with the intensification but the less energetic flux enhancements (as recorded by TH-C) before the intensification were not recorded (not shown). Figure 2l shows two energy channels from LANL-97A. Accounting for time delays of about 30 s and 52 s, the initial injections are similar to those recorded by TH-C (dashed lines). The different time delays indicate that the energy was dispersed at the location of LANL-97A which is generally thought to be due to the azimuthal ion drift during the earthward transport of the ion injection. This typical dispersion signature together with the observations at TH-C lead us to conclude that the energetic injections were indeed transient events which is different from the lower energy flux enhancements observed at TH-C which are suggestive of simple up and down motion of the heated plasma sheet as described above.

[9] Figures 2i and 2j show the transverse magnetic field components (in mean-field-aligned coordinates) from TH-C. Both  $B_x$  and  $B_y$  show a strong magnetic pulse near the onset of the ion injections (first red line from the left) which we interpret as the magnetic signature of a filamentary current located in the hot plasma boundary which is moving with respect to the spacecraft. Smaller transverse perturbations of  $B_x$ , following the large pulse, are correlated with the  $B_z$  component (see, e.g., second and third red dashed lines). This correlation can again be due to the signature of a filamentary current structure in the boundary. Thus, the

**Figure 2.** Comparison of space (TH-C and LANL-97A) and ground magnetometer data. (a) Azimuth-time spectrogram of ions with energy  $>200$  keV; (b, c) ion energy-time spectrograms; (d) azimuth-time spectrogram of ions with  $E > 40$  keV, solid and dashed white lines indicate the total magnetic field azimuth in the parallel and anti-parallel directions to the field line, respectively; (e–g) differential energy flux for various energy channels; (h–j) magnetic field [Auster *et al.*, 2008] in mean-field aligned coordinates; (k, l) selected energy channels from TH-C and LANL-97A; and (m–q) filtered ground magnetometer data (40 s, 200 s).

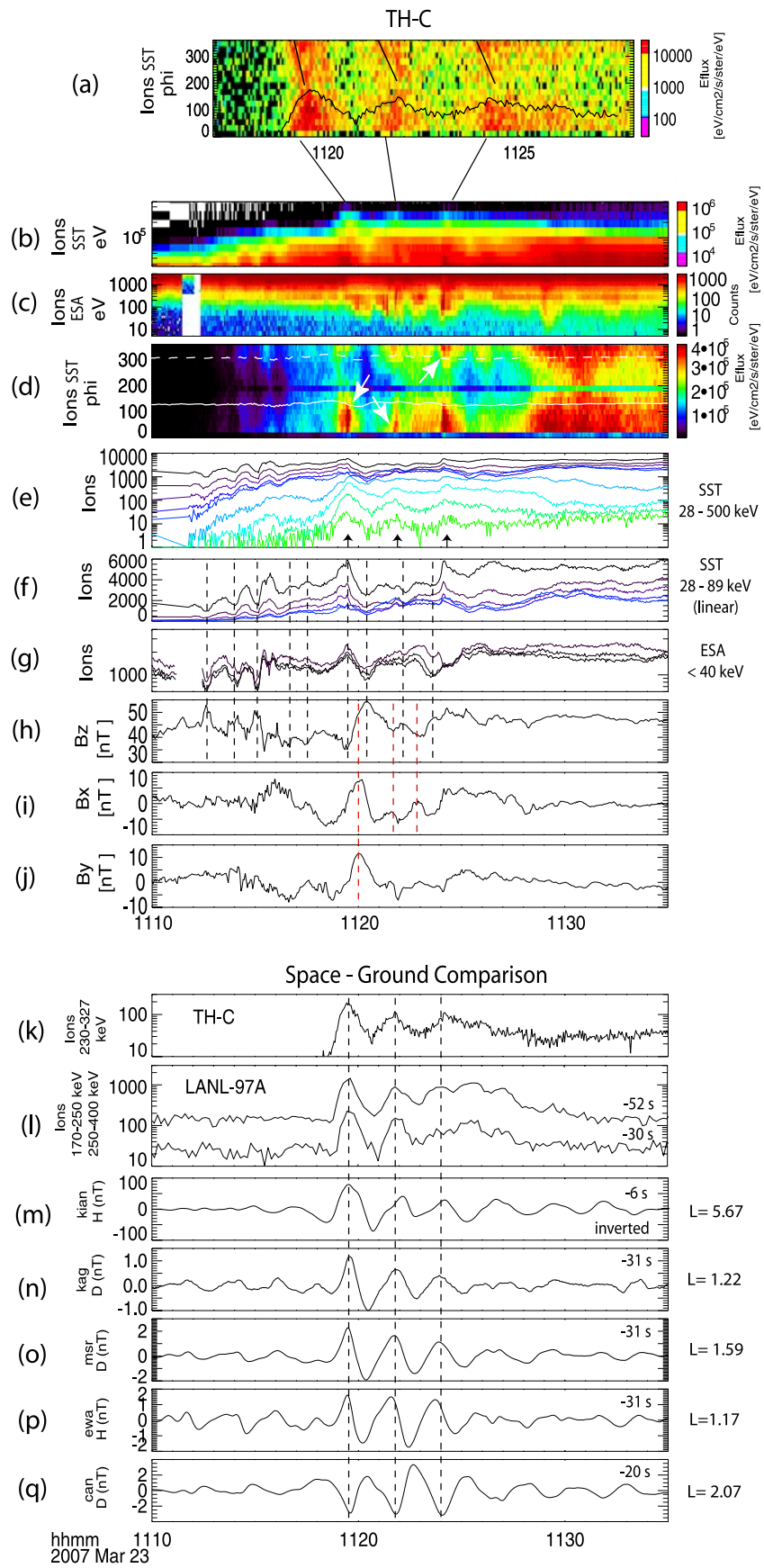
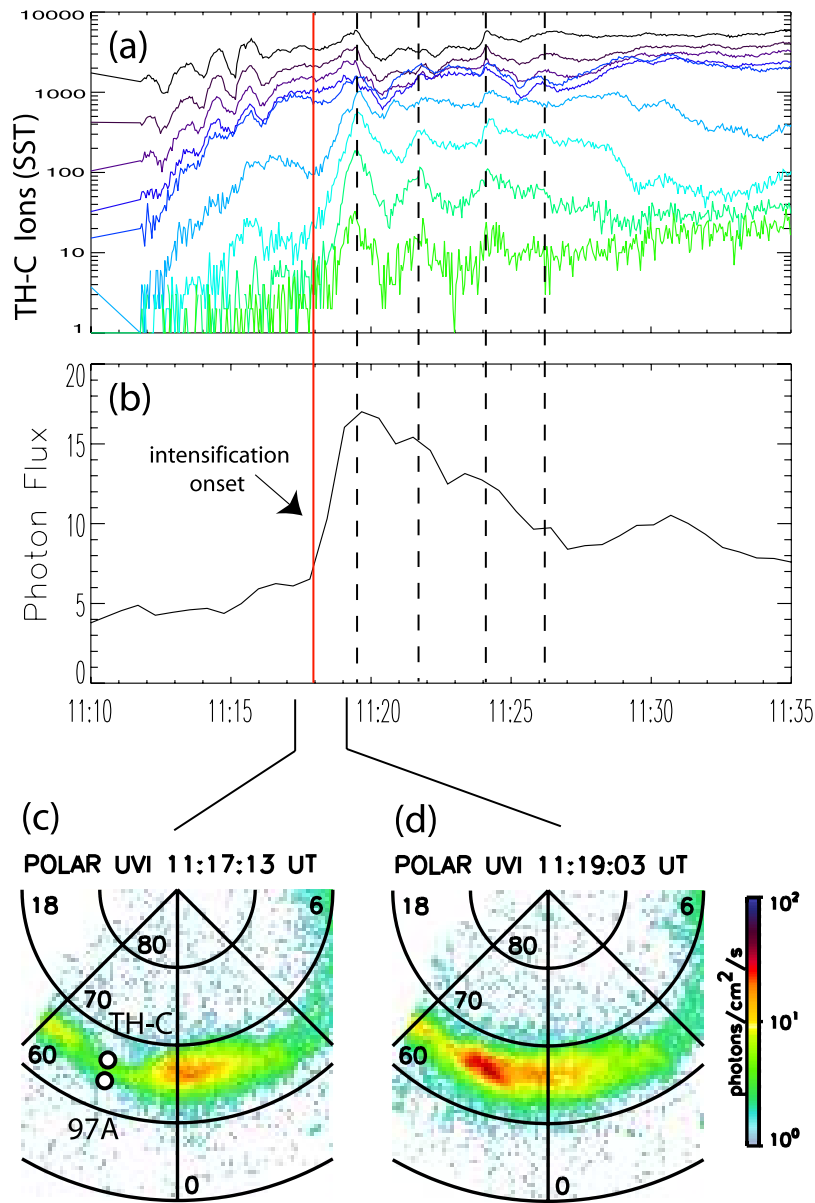


Figure 2



**Figure 3.** Comparison of (a) ion injection data recorded by TH-C and (b) auroral luminosity modulations. The photon flux was averaged at 65° latitude spanning the sector 21 to 0 MLT which covers the region of auroral intensification. (c, d) Two UVI images taken before and after the intensification; the footprints of TH-C and LANL-97A are indicated by open circles.

transverse perturbations appear to be largely controlled by the boundary motion – as was  $B_z$  – of the lower energetic plasma (<100 keV) and not the energetic (>100 keV) ion injections. We conclude that there is no one-to-one correlation of magnetic field perturbations and the energetic ion injections, a fact which will be important later on when discussing the source of the ground Pi2.

[10] Next we compare the in-situ signatures with ground magnetometer data. The ground data in Figure 2 are from Kiana (KIAN, Alaska), Ewa Beach (EWA, Hawaii), Kagoshima (KAG, Japan), Moshiri (MSR, Japan), and Canberra (CAN, Australia) which cover  $\sim 4$  hours of local time and  $L$  values from 1.17 to 5.67 including one station (CAN) in the Southern Hemisphere. The ground data in Figures 2m–2q are band-pass filtered (40–200 s which

comprises the Pi2 frequency band) and show well developed Pi2 pulsations. Either the  $H$  or  $D$  component is plotted depending on which one was the strongest signal. Whereas  $H$  was in phase at low-latitude stations (not shown for all stations),  $D$  was out phase between the two hemispheres (e.g., KAG and CAN). All ground data were time-shifted by various amounts so that their major peaks line up with the peaks of the flux enhancements at TH-C (Figures 2k). There is a good match among the peaks of the ground and space variations (see vertical dashed lines; it is noted that EWA possibly shows a slightly smaller period). For completeness, it is mentioned that other THEMIS ground stations located to the east of KIAN (which is the most western THEMIS station) did not record the same ground Pi2 (not shown). The only other station of the THEMIS ground network

which recorded the same Pi2 was McGrath (MCGR,  $\delta H \sim 20$  nT, not shown) which was located  $\sim 5^\circ$  south of KIAN on approximately the same meridian and there was no noticeable time delay between KIAN and MCGR. All other stations that recorded the same Pi2 were located west of KIAN and showed various time delays. Moreover, it is important to note that the Pi2 at the high-latitude station KIAN showed extremely large amplitudes ( $\delta H \sim 150$  nT) and there was only a 6-s time delay between the periodic in-situ particle injections and the ground Pi2 at KIAN, which was closest to the foot point of TH-C at the time of Pi2 onset. These observations show that the ground Pi2 were observed over a wide range and that propagation effects (possibly due to compressional waves crossing magnetic field lines) were present. Finally, it is noted that the magnetic field variations at TH-C did not show the same periodicity as the ground Pi2 which is due to the fact that the magnetic field oscillations were coupled to the oscillatory behavior of the lower energetic ( $<100$  keV) plasma (see above).

[11] Figure 3 shows a comparison of ion energy flux recorded by TH-C and averaged photon flux from global Polar-UVI images. The photon flux was averaged at  $65^\circ$  latitude spanning the sector 21 to 0 MLT which covers the region of the auroral intensification (Figure 3d). The averaged photon flux shows modulations after the intensification onset which correlate with the variations of the energy flux of the most energetic ions (dashed lines). Moreover, the onsets of both auroral intensification and ion injection coincided within the time resolution of the UVI imager ( $\sim 36$  s). Figures 3c and 3d show two UVI images, taken before and after the intensification. The footprints of TH-C and LANL-97A are indicated by open circles. The mapping is partially based on the MHD simulation by *Raeder et al.* [2008], and on the fact that strong ion upflow was observed by TH-C, which is a signature of active auroral field lines (cf. Figure 1).

### 3. Discussion and Conclusions

[12] This case study presents for the first time a one-to-one correlation among low and high-latitude ground Pi2 pulsations, auroral modulations, and periodic ion injections beyond geosynchronous orbit. Owing to the extremely large amplitude ( $\delta H = \sim 150$  nT) of the high-latitude Pi2, it could be argued that they were in fact a series of individual ground intensifications, and as such each *H*-bay “pulse” would be associated with a near-Earth ion injection as observed by TH-C. Since these injections occurred periodically, the ground experienced corresponding periodic *H*-bay perturbations. Furthermore, during the periodic ion injections, TH-C was conjugate to the region of auroral brightening which was modulated with the same period as the injections. These combined observations clearly demonstrate that the three substorm phenomena had a common source which controlled their periodicity. However, it remains open as to what this source was. *Kepko and Kivelson* [1999] reported periodic bursty bulk flows and *Keiling et al.* [2006] reported periodic reconnection pulses at Pi2 frequency, both of which were correlated with ground Pi2. In both scenarios the driver is located in the distant magnetotail. Alternatively, it might be a local instability near the inner edge of the

plasma sheet as described, for example, by *Cheng* [1991] that leads to large-scale plasma sheet oscillations and possibly periodic ion injections. It was also found here that only those ions with the highest energies ( $>100$  keV) showed the specific Pi2-frequency modulation whereas the lower energetic ions executed different oscillations - apparently independent of the most energetic particles - and thus were not related to the ground signatures. Therefore, it can be concluded that the energization process of the most energetic particles was responsible for the periodic signatures and not the oscillations of the “bulk” plasma sheet. Furthermore, the plasmasphere can be ruled out as a possible source for the correlated intense Pi2 signals which were observed in both inner and outer magnetosphere. We also find it unlikely that the transient response mechanism (e.g., review by *Baumjohann and Glassmeier* [1984]) operated in which case the Alfvén bounce time would determine the Pi2 frequency (see below).

[13] For the various space and ground Pi2 signatures, we reported different time delays among them which provide some suggestions as to what drove the ground signatures. Importantly, there was only a 6-s time delay between in-situ ion injections and high-latitude Pi2. The Alfvén transit time from the near-Earth plasma sheet to the ionosphere is about 30–60 s, which rules out that Alfvén waves propagated from the location of the spacecraft to the ground causing the ground Pi2; no such periodic Alfvén waves were observed at TH-C either. On the other hand, energetic particles with energies  $>100$  keV take only  $<10$  s for the same path. Hence, it appears possible that the ion injections were causally related to the high-latitude ground Pi2s. In support of this, it was further noted that the footprint of TH-C was in the proximity of the high-latitude station which recorded the largest Pi2. Similarly, one might argue that the periodic ion injections were possibly causally related (via intermediate energy transfer processes) to the auroral modulations. However, one reason for caution is that it is not known with certainty when the ion injections occurred. Because the hot plasma boundary was not only moving towards Earth but also expanding toward the spacecraft (i.e., southward), it could be speculated that the injections occurred, e.g., 30 s earlier and then expanded outward toward TH-C. In this scenario, the short time delay of 6 s would merely be a coincidence, and there would possibly be enough time for an Alfvén front - which might be launched during the ion injection process - to carry a field-aligned current to the ground to cause a substorm bay. The successive launching of Alfvén fronts (from a site located somewhat removed from the spacecraft) at intervals of 135 s would then lead to the observed ground Pi2 at high latitude. If this scenario is correct, it would still rule out the transient response mechanism which results in much smaller amplitudes of ground Pi2 and which would be independent of the periodicity associated with the substorm injection mechanism for this event. Finally, the global spreading of the Pi2 signal to low latitudes covering a large region both in latitude and longitude was likely caused by the cross-field propagation of fast mode waves inside the plasmasphere which would also account for the longer time delays (20–31 s). The polarization of the ground oscillations (in-phase *H* and out-of-phase *D* components at low latitudes at both hemi-

spheres) is in fact suggestive of such waves propagating westward from a meridian that contains TH-C.

[14] Finally, we bring to the reader's attention that the here reported one-to-one correlation of substorm-associated ion injections, auroral modulations and low- to high-latitude ground Pi2 could be related to observations reported by Saka *et al.* [1999] who showed such one-to-one correlation for geosynchronous ion flux enhancements and individual pulses in a Pi2 train at low latitude (dip equator) separated by five hours of local time from the in-situ observations. The ground Pi2 pulsations were also correlated with optical modulations. However, these observations also showed significant differences to ours such as that no mid- to high-latitude ground data were available, the correlated signals did not occur at substorm onset/intensification but later in the substorm, and it is not clear whether the flux enhancements at geosynchronous orbit were ion injections.

[15] **Acknowledgments.** This work was supported by the NASA THEMIS project. The work of the IGEP team at the Technical University of Braunschweig was financially supported by the German Ministerium für Wirtschaft und Technologie and the German Zentrum für Luft- und Raumfahrt under grant 50QP0402. We thank the LANL and the 210 MM science teams for making their data available.

## References

- Angelopoulos, V. (2008), The THEMIS mission, *Space Sci. Rev.*, in press.
- Angelopoulos, V., et al. (2008), First results from the THEMIS mission, *Space Sci. Rev.*, in press.
- Auster, H. U., et al. (2008), The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, in press.
- Baumjohann, W., and K. H. Glassmeier (1984), The transient response mechanism and Pi2 pulsations at substorm onset: Review and outlook, *Planet. Space Sci.*, 32, 1361.
- Cheng, C. Z. (1991), A kinetic-magnetohydrodynamic model for low-frequency phenomena, *J. Geophys. Res.*, 96, 21,159.
- Keiling, A., et al. (2006), Association of Pi2 pulsations and pulsed reconnection: Ground and Cluster observations in the tail lobe at 16 RE, *Ann. Geophys.*, 24, 3433.
- Kepko, L., and M. G. Kivelson (1999), Generation of Pi2 pulsations by bursty bulk flows, *J. Geophys. Res.*, 104, 25,021.
- Liou, K., C.-I. Meng, P. T. Newell, K. Takahashi, S.-I. Ohtani, A. T. Y. Lui, M. Brittner, and G. Parks (2000), Evaluation of low-latitude Pi2 pulsations as indicators of substorm onset using Polar ultraviolet imagery, *J. Geophys. Res.*, 105, 2495.
- Liou, K., C.-I. Meng, P. T. Newell, A. T. Y. Lui, G. D. Reeves, and R. D. Belian (2001), Particle injections with auroral expansions, *J. Geophys. Res.*, 106, 5873.
- Raeder, J., et al. (2008), OpenGGCM simulations for the THEMIS mission, *Space Sci. Rev.*, in press.
- Saka, O., et al. (1999), A slow mode wave as a possible source of Pi2 and associated particle precipitation: A case study, *Ann. Geophys.*, 17, 674.
- Yeoman, T. K., M. P. Freeman, G. D. Reeves, M. Lester, and D. Orr (1994), A comparison of midlatitude Pi2 pulsations and geostationary orbit particle injections as substorm indicators, *J. Geophys. Res.*, 99, 4085.
- V. Angelopoulos, J. W. Bonnell, C. Carlson, M. Fillingim, H. Frey, S. Frey, A. Keiling, D. Larson, R. Lin, J. McFadden, S. Mende, F. S. Mozer, G. Parks, and T. Phan, Space Sciences Laboratory, University of California, Berkeley, CA 94720–7450, USA. (keiling@ssl.berkeley.edu)
- H. U. Auster and K.-H. Glassmeier, Institut für Geophysik und Extraterrestrische Physik, Technische Universität Braunschweig, D-38106 Braunschweig, Germany.
- E. Donovan, Department of Physics and Astronomy, University of Calgary, Calgary, AB, Canada T2N 1N4.
- O. LeContel and A. Roux, CETP, IPSL, 10–12 Avenue de l' Europe, F-78140 Velizy, France.
- X. Li and W. Liu, LASP, University of Colorado, Boulder, CO 80303, USA.
- W. Magnes, Space Research Institute, Austrian Academy of Science, A-8042 Graz, Austria.
- I. Mann, Department of Physics, University of Alberta, Edmonton, AB, Canada T6G 2J1.
- C. T. Russell, Department of Physics, University of California, Los Angeles, CA 90095–1567, USA.
- J. Raeder, Space Science Center, University of New Hampshire, Durham, NH 03824, USA.
- K. Shiokawa, Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa, 442–8507, Japan.