Local time-dependent Pi2 frequencies confirmed by simultaneous observations from THEMIS probes in the inner magnetosphere and at low-latitude ground stations

H.-J. Kwon,[1] K.-H. Kim,[1] D.-H. Lee,[1] K. Takahashi,[2] V. Angelopoulos,[3] E. Lee,[1] H. Jin,[1] Y.-D. Park,[4] J. Lee,[4] P. R. Sutcliffe,[5] and H. U. Auster[6]

Received 8 May 2011; revised 16 November 2011; accepted 21 November 2011; published 7 January 2012.

[1] Using electric and magnetic field data from Thermal Emission Imaging System (THEMIS) probes (TH-A, TH-D, and TH-E) acquired in the inner magnetosphere ($L < 4$) and low-latitude ground magnetic field data from Bohyun (BOH, $L = 1.35$) and Hermanus (HER, $L = 1.83$) stations, we studied longitudinal variations of Pi2-associated fast mode waves away from midnight. We selected 48 nightside Pi2 events at BOH identified when THEMIS probes were in the inner magnetosphere for 1 month (February 2008). During that period the probes were located between 4.0 and 20.0 magnetic local time (MLT), i.e., at and on either side of the dayside sector. This choice was motivated by our interest in studying loss of Pi2 wave energy away from its nominal source at the nightside, all the way to the dayside. Between 4.0 and 8.0 MLT the probes often observed poloidal oscillations in space during BOH Pi2 events. The poloidal oscillations had high coherence (>0.6) with BOH Pi2s and radially standing fast mode structures. Thus, these fast mode waves are explained by plasmaspheric resonance. On the duskside, however, few events at THEMIS probes had high coherence with BOH Pi2s. Furthermore, the THEMIS probe data showed no evidence of Pi2 signals at 9.0–18.0 MLT, which is consistent with previous studies. Most of the high-coherence events were detected when the local time separation between the THEMIS probes and BOH was less than 3 h. These observations suggest that Pi2 wave energy is lost as it propagates azimuthally from a source region localized in longitude. From longitudinally separated simultaneous multipoint observations at THEMIS probes and BOH and HER stations, we found that the Pi2 frequency varies with longitude both in space and on the ground. This implies that although plasmaspheric fast mode waves establish a standing wave structure on a given meridional plane, their frequency changes with longitude if the plasmasphere is not axisymmetric. Finally, we show that a low-latitude daytime Pi2 is not a fast mode wave propagating to the dayside through the magnetosphere.

Citation: Kwon, H.-J., et al. (2012), Local time-dependent Pi2 frequencies confirmed by simultaneous observations from THEMIS probes in the inner magnetosphere and at low-latitude ground stations, *J. Geophys. Res.*, *117*, A01206, doi:10.1029/2011JA016815.

1. Introduction

[2] Pi2 magnetic pulsations (period of 40–150 s) are excited at expansion phase onset or intensification of a geomagnetic substorm [*Saito*, 1969]. Low-latitude and mid-latitude Pi2 pulsations have been suggested to be magnetic field perturbations corresponding to fast mode waves trapped in the plasmasphere [*Yeoman and Orr*, 1989]. The presence of trapped waves (i.e., plasmaspheric resonance) has been directly confirmed from spacecraft observations in the inner magnetosphere using electric and magnetic field as well as plasma density measurements [*Takahashi et al.*, 1995, 2001, 2003].

[3] Plasmaspheric resonance can be established when there is a sharp inward density gradient at the plasmapause [e.g., *Allan et al.*, 1986; *Zhu and Kivelson*, 1989; *Lee*, 1996]. Thus, the size and shape of the plasmasphere play a crucial role in determining the properties of fast mode waves trapped inside it. Plasmaspheric resonance frequency is determined by the size of the plasmasphere and the Alfvén speed. *Takahashi et al.* [2003] and *Nosé* [2010] showed that plasmaspheric

[1]School of Space Research, Kyung Hee University, Yongin, South Korea.
[2]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.
[3]IGPP, University of California, Los Angeles, California, USA.
[4]Solar and Space Weather Research Group, Korea Astronomy and Space Science Institute, Daejeon, South Korea.
[5]South African National Space Agency Space Science, Hermanus, South Africa.
[6]IGEP, Technical University of Braunschweig, Braunschweig, Germany.

0148-0227/12/2011JA016815

resonance Pi2 oscillation frequency decreases as the plasmapause distance from Earth increases.

[4] For the case of an idealized fundamental plasmaspheric cavity mode, the radial and north–south mode structures give a standing structure. This means that the relative phase of compressional magnetic field (δB_z) between radially separated arbitrary points in a cavity should be 0° or 180°, provided measurements are made on the same meridian. The azimuthal electric field (δE_y) is ±90° out of phase with δB_z. These cavity mode phase properties were reported from satellite observations in the inner magnetosphere [e.g., *Takahashi et al.*, 2001, 2003].

[5] According to *Sutcliffe and Yumoto* [1989, 1991], low-latitude Pi2 pulsations occur almost simultaneously on both dayside and nightside and have nearly identical frequency and waveform. They argued that these pulsations are excited as a single plasmaspheric resonance mode commonly observed at all longitudes. Longitudinal Pi2 frequency changes have been observed at low-latitude ground stations, however [*Kosaka et al.*, 2002; *Han et al.*, 2003; *Takahashi and Liou*, 2004]. According to these ground observations, premidnight Pi2 frequencies are statistically lower than those in the postmidnight. Such a longitudinal Pi2 frequency change would be interpreted as resonance excited in a plasmasphere with dawn-dusk asymmetry (i.e., larger plasmapause distance in the dusk sector than in the dawn sector).

[6] In a numerical and analytical study, *Lee* [1996] suggested that azimuthal harmonics can be defined after a relatively long time when the wave front arrives at the opposite side of a wave source region and that cavity mode frequencies are less affected by different azimuthal wave numbers because the azimuthal direction allows a relatively large wavelength in dipole geometry. Thus, two-dimensional compressional discrete modes will appear in the meridional plane before the wave energy disappears. A numerical study by *Fujita and Itonaga* [2003] reported that the dominant frequency of plasmaspheric resonance varies with longitude in an asymmetric plasmasphere.

[7] *Kim et al.* [2010] examined the longitudinal variations of Pi2 pulsations for individual Pi2 events observed simultaneously by the Thermal Emission Imaging System (THEMIS) E (TH-E) and D (TH-D) probes in the dawn and dusk sectors, respectively, of the inner magnetosphere. On the dawnside, TH-E observed Pi2-associated poloidal oscillations exhibiting properties of radially standing fast mode waves. On the duskside, however, TH-D detected no poloidal oscillations in the Pi2 frequency band. *Kim et al.* [2010] suggest that there is strong longitudinal attenuation of fast mode waves near the duskside, perhaps due to complicated duskside plasmapause structures. These longitudinal variations in Pi2 frequency and waveform may explain why high-coherence events did not occur near dusk [*Takahashi et al.*, 2003] and why Pi2-associated poloidal oscillations in the dayside have low coherence with low-latitude Pi2 pulsations in the nightside.

[8] There are a number of studies of the radial mode structure of plasmaspheric Pi2 pulsations from spacecraft observations. Only *Kim et al.* [2010], however, have studied longitudinal variations of Pi2-associated fast mode waves away from midnight using electric and magnetic field data from multisatellite observations in the inner magnetosphere ($L < 4$), and little attention has been paid to Pi2-associated fast mode waves on the dawnside and duskside. In this study, we examine electric and magnetic field perturbations observed by multiple THEMIS probes in the inner magnetosphere ($L < 4$) and Pi2 pulsations observed at the low-latitude Bohyun (L = 1.35) station. We extend the study by *Kim et al.* [2010] to statistically investigate the mode structure in the dawn and dusk sectors and the propagation of Pi2 pulsations away from midnight. Simultaneous observations at longitudinally separated points in space allow us to determine the longitudinal coherence scale and whether Pi2 signal localization occurs in the inner magnetosphere's meridional plane.

[9] This paper is organized as follows. In section 2 we briefly describe the data sets used in this study and the event selection procedure. We present a case study in section 3. In section 4 we show statistical results of Pi2 pulsations, and in section 5 we analyze these results.

2. Data

2.1. Data Set

[10] Electric [*Bonnell et al.*, 2008] and magnetic [*Auster et al.*, 2008] field data measured by TH-A, TH-D, and TH-D [*Sibeck and Angelopoulos*, 2008] in the inner magnetosphere ($L < 4$) and magnetic field data measured on the ground at Bohyun (BOH), Korea, and Hermanus (HER), South Africa, during the month of February 2008 are used in this study. THEMIS probes measure the electric field only in their spin plane (approximately GSE *X-Y*). The third component, directed along the spin axis, can be obtained by assuming no electric field **E** along the ambient magnetic field **B**; that is, $\mathbf{E} \cdot \mathbf{B} = 0$. To study Pi2 pulsations, we use spin averages (~3 s) of the electric and magnetic field data. The spin fit field data were exactly resampled at 3 s intervals after interpolation.

[11] The THEMIS field data are presented in mean-field-aligned coordinates. In this system, $\hat{e}_z$ is along the magnetic field defined by taking 5 min boxcar running averages of the 3 s data; $\hat{e}_y$ (eastward) is parallel to $\hat{e}_z \times \mathbf{r}$, where $\mathbf{r}$ is the spacecraft position vector with respect to the center of the Earth; and the radially outward component is given by $\hat{e}_x = \hat{e}_y \times \hat{e}_z$. The transverse components δB_x and δB_y are high-pass-filtered perturbations by definition, and the parallel component δB_z is defined as B_z (3 s averages) minus B_z (5 min averages). Likewise, the perturbed electric field is defined as $E_{x,y}$ (3 s averages) minus $E_{x,y}$ (5 min averages). As stated above, the parallel electric field δE_z is assumed to be zero.

[12] Magnetic field measurements from the BOH station are used to detect low-latitude Pi2 pulsations. BOH is located at 29.8° magnetic latitude (L = 1.35), 36.2° geographic latitude, and 128.9° geographic longitude. The geomagnetic magnetic field measurements at BOH were made with a fluxgate magnetometer, which acquires vector samples every second at 0.01 nT resolution. We reduced the time resolution of the data to 3 s by taking three-point running averages of the 1 s data. We also use low-latitude magnetic field data from the HER station, which is separated by about 8 h local time from the BOH station. HER is located at −42.42° magnetic latitude (L = 1.83), −34.4° geographic latitude, and

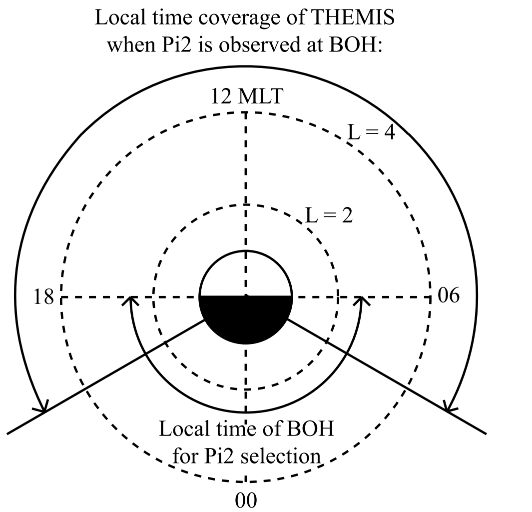

Figure 1. Magnetic local time (MLT) versus dipole L plot of the spatial coverage of Bohyun ground data and THEMIS probe data for selected Pi2 events. The THEMIS data were used when the probes were at distances $L < 4$.

19.2° geographic longitude. HER provides induction magnetometer data at 1 s resolution. The induction magnetometer data were made equivalent to fluxgate magnetometer data (nT units) using an experimentally determined frequency response sensor function. HER 1 s data were also resampled at 3 s intervals.

2.2. Event Selection

[13] Pi2 pulsations were identified from the H (positive northward) component of the BOH magnetic field data. To select Pi2 events we applied the automated procedure developed by *Takahashi et al.* [1995] to the BOH H data acquired when BOH was located on the nightside from 18.0 to 6.0 MLT. During this period, the THEMIS probes were between 4.0 and 20.0 MLT in the inner magnetosphere ($L < 4$), as shown in Figure 1. Thus, we can compare nightside low-latitude Pi2 pulsations to corresponding magnetic and electric field perturbations in the inner magnetosphere away from midnight, including the noon sector. To avoid duplicating previous statistical studies [*Takahashi et al.*, 1995, 2003], we will not elaborate on Pi2-associated field perturbations in the nightside inner magnetosphere from 20.0 to 4.0 MLT. The AL index (with a 1 min time resolution) was used to examine substorm-associated geomagnetic activity.

[14] We identified 48 BOH Pi2 events in February 2008. Figure 2 shows the equatorial projection of THEMIS probe locations at the time of ground Pi2 pulsations. Note that there are 62 data points in Figure 2 because some events were observed simultaneously by two probes. Figure 3 shows the distribution of THEMIS probe observation time in February 2008 versus MLT for two BOH local time ranges, premidnight between 18.0 and 24.0 MLT and postmidnight between 24.0 and 6.0 MLT. In this study we examine Pi2 signal correlation between nightside on the ground at BOH and dayside, dawn, and dusk in space at THEMIS. TH-D and TH-E have no observations between 4.0 and 20.0 MLT in the inner magnetosphere ($L < 4$) when BOH was in the local time range between 18.0 and 24.0 MLT. Thus, most THEMIS data were available when BOH was in the postmidnight.

3. Examples of Simultaneous THEMIS Probe and Low-Latitude Ground Observations

[15] In this section, we present four events (one on 14 February 2008 and three on 16 February 2008) recorded simultaneously by THEMIS probes and low-latitude ground stations.

3.1. The 14 February 2008 Event

[16] Figures 4a, 4b, and 4c show the AL index and the ground magnetic field components of H (northward) and D (eastward) at BOH for a 1 h interval (1900–2000 UT) on 14 February 2008. A small decrease in AL occurred at 1908 UT and then it recovered to −116 nT. From 1914 to 1942 UT, AL gradually decreased to −490 nT. The horizontal components at BOH exhibit significant baseline changes, a positive increase (positive bay) in H occurred at ∼1908 UT and ∼1930 UT, respectively. The positive bay was accompanied by a negative bay in the D component, which can be attributed to the substorm current wedge [*Clauer and McPherron*, 1974]. The negative D perturbation implies that BOH was located east of the center of the substorm current wedge. Figures 4b and 4c show Pi2 pulsations superposed on the background changes. These are classical low-latitude features associated with substorm activity. The Pi2 pulsation described in this case study occurred around 1932 UT, marked by the vertical dashed line.

[17] The locations of the THEMIS probes and low-latitude ground stations at the onset of the Pi2 event are plotted in

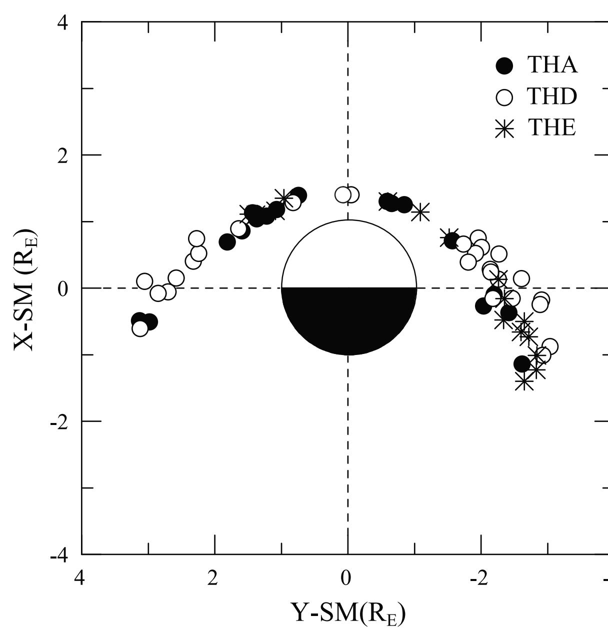

Figure 2. Equatorial projection of THEMIS probe positions at times of the Pi2 pulsations identified at BOH during February 2008. The solid circles, open circles, and asterisks indicate the positions of TH-A, TH-D, and TH-E, respectively.

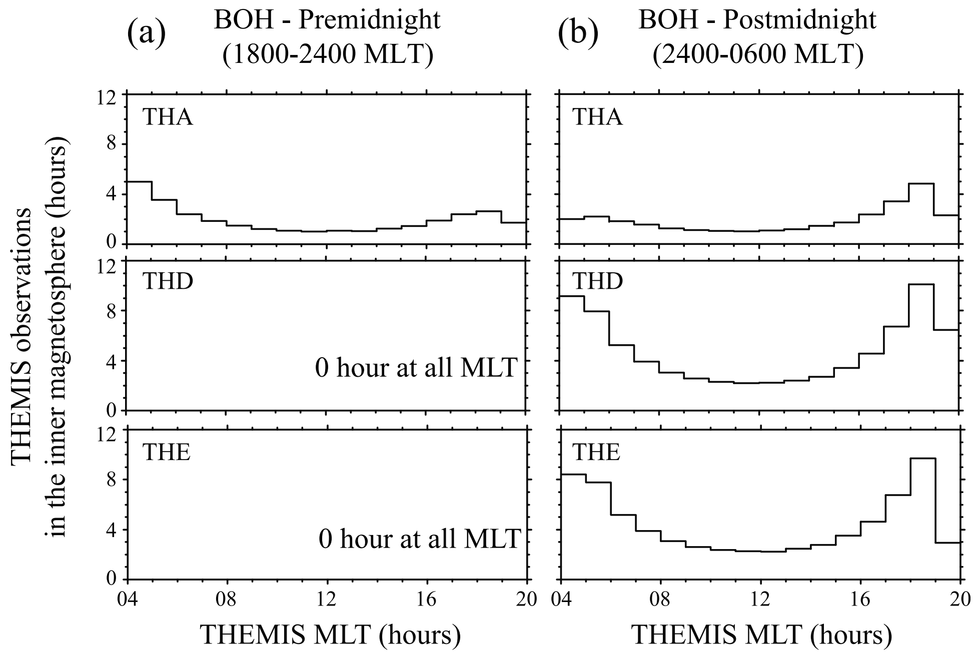

Figure 3. Distribution of THEMIS probe observations in the inner magnetosphere ($L < 4$) versus MLT for two BOH local time ranges: (a) premidnight between 18.0 and 24.0 MLT and (b) postmidnight between 24.0 and 6.0 MLT.

Figure 4d. TH-A was in the dawnside inner magnetosphere (L = 2.9, MLT = 5.3) and south of the magnetic equator (MLAT = −18.5°). TH-D was in the duskside inner magnetosphere (L = 2.8, MLT = 18.0) and north of the magnetic equator (MLAT = 11.8°). The BOH (L = 1.35) station was located in the postmidnight sector (MLT = 3.8), and the HER (L = 1.83) station was located in the premidnight sector (MLT = 20.1).

[18] Figure 5a shows the time series plots of δH at BOH and HER, which are 3 s samples with 300 s running averages removed. The vertical dashed lines indicate the peaks of δH at BOH. Pi2 band (40–150 s) oscillations are present at both ground stations throughout the 10 min interval 1932–1942 UT. Although the oscillations at BOH and HER were initially in phase, their relative phase increased gradually over 3 cycles, indicating that the frequency in the postmidnight sector is higher than that in the premidnight sector. At 1936 UT the oscillations were in phase, and then the phase at BOH led that at HER at 1938 and 1939 UT. The oscillations were in phase again at 1940 UT. The solid dots above the time series of δH at BOH indicate the start time of the in-phase oscillation. From careful examination of the *AL* index, small *AL* slope changes are found at around 1936 and 1940 UT. Thus, we suggest that the observed Pi2 oscillations were associated with high-latitude disturbances during a substorm. The oscillations lasted 3–4 cycles with a higher frequency in the postmidnight sector than in the premidnight sector.

[19] Figures 5b and 5c show the autopower spectra for the H components at BOH and HER for the 15 min (1930–1945 UT) and 4 min (1932–1936 UT) intervals, respectively. The horizontal bar in each plot indicates a resolution bandwidth for each frequency value after averaging over five raw spectral estimates. Figure 5d shows the coherence between BOH δH and HER δH for the 15 min interval 1930–1945 UT (solid circles) and the 4 min interval 1932–1936 UT (open circles). Coherence is defined as the ratio of the cross-power spectrum to the square root of the product of the autopower spectra in a given frequency band for two time series. The coherence was also obtained by averaging over five raw spectral estimates, leading to 10 degrees of freedom. The normalized errors of the coherence, 0.7, 0.8, and 0.9, estimated using five spectral averages, are 0.46, 0.28, and 0.13, respectively [*Bendat and Piersol*, 2010]. The BOH and HER spectra differ slightly. The BOH δH spectrum is enhanced in the frequency band 15–20 mHz, whereas the HER δH spectrum is enhanced at 10–20 mHz. As expected from the time series plot in Figure 5a, the HER spectrum shows a broad peak that is shifted to left relative to the peak in the BOH spectrum. Although BOH δH and HER δH do not have identical periods over two or three cycles, the coherence for the 15 min interval 1930–1945 UT is higher than that for the 4 min interval 1932–1936 UT because the coherence is calculated for a time interval longer than three cycles and the amplitude ratio for two signals is relatively constant. Thus, coherence analysis alone does not allow us to claim that the same signal is excited at different local times.

[20] Because the polarization state of magnetospheric waves cannot be determined from ground-based observations, spacecraft observations are necessary to examine the properties of magnetic and electric field perturbations in space that correspond to ground Pi2 pulsations. To learn whether the fast mode waves were directly detected on the ground, we compare the low-latitude horizontal H component on the ground and the poloidal components in space, characterized by the azimuthal oscillation of the electric field (δE_y) and the radial (δB_x) and compressional (δB_z) oscillations of the magnetic field in Figure 6. The vertical dashed

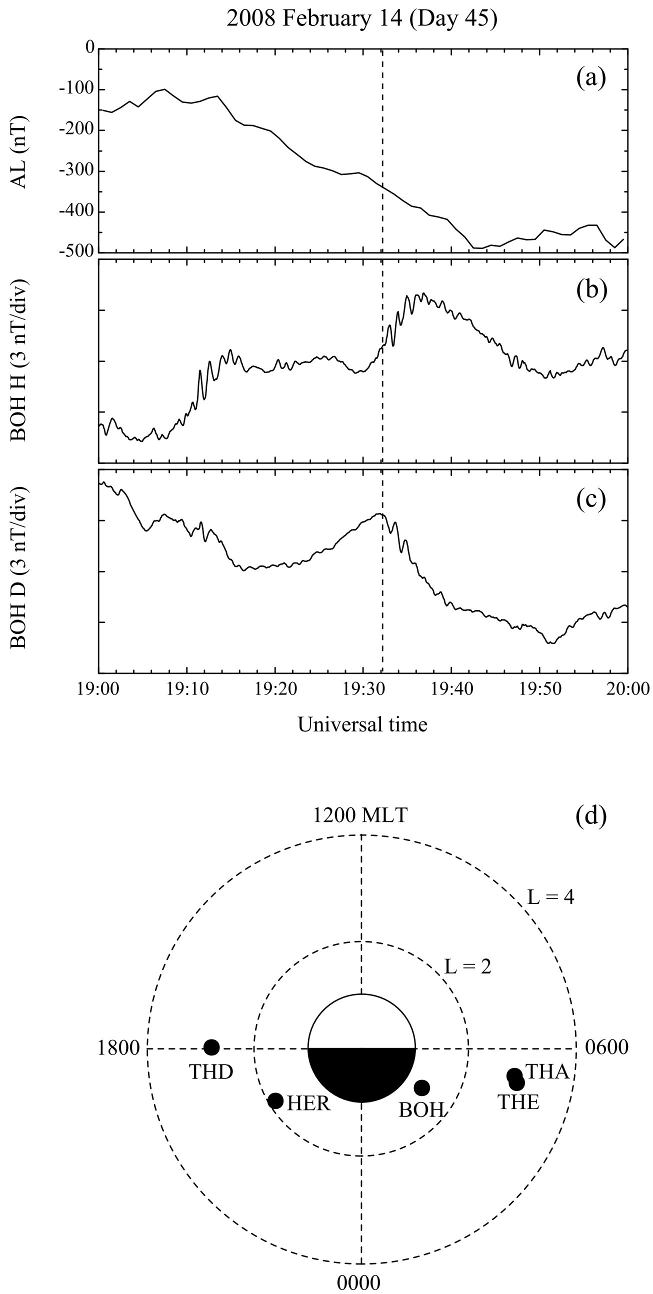

Figure 4. (a) The auroral electrojet *AL* index, (b) the *H* and (c) *D* components at Bohyun station from 1900 to 2000 UT on 14 February 2008. The vertical dashed line indicates Pi2 onset at 1931 UT on 14 February 2008. (d) MLT and *L* plot of the locations of THEMIS probes and low-latitude ground stations at the Bohyun Pi2 onset time.

lines in Figures 6a and 6b indicate the δH peaks at BOH and HER, respectively. Note that the amplitudes of TH-A δE_y and HER δH are reduced to 50% of the original.

[21] As shown in Figure 6a, TH-A, which was located in the dawnside inner magnetosphere (L = 2.9, MLT = 5.3) below the equator (MLAT = −18.5°), observed a compressional (δB_z) oscillation with period and waveform nearly identical to those of the *H* component oscillation at BOH in the postmidnight sector (MLT = 3.8) with a local time difference of ~1.5 h from TH-A. This indicates that the oscillations at BOH and TH-A are excited by a common generation mechanism. The radial magnetic field component, δB_x, at TH-A oscillates out of phase with δB_z. Following the vertical dashed lines in Figure 6a, the δB_z peaks are found to lead the δE_y peaks by a quarter of the wave period, which is equivalent to a phase delay of ~90°. These phase relationships among the poloidal components (δB_x, δB_z, and δE_y) are consistent with a radially standing oscillation of the fundamental mode [*Kim and Takahashi*, 1999; *Takahashi et al.*, 2001, 2003]. We note that δB_x is larger than δB_z by a factor of ~4, perhaps because TH-A was near the node in the fundamental mode δB_z perturbation.

[22] Figure 6b shows that the waveform of the poloidal magnetic field components (δB_x and δB_z) at TH-D, located in the duskside inner magnetosphere (L = 2.8, MLT = 18.0) above the equator (MLAT = 11.8°), is nearly identical to δH at HER, located in the premidnight sector (MLT = 20.1). The high degree of similarity in waveform between TH-D and HER is also attributed to a common generation mechanism. Since TH-D was above the equator, the radially standing poloidal oscillation of the fundamental mode will show a 0° phase delay between δB_x and δB_z and a 90° phase shift between δE_y and the poloidal magnetic field components. Unlike TH-A on the dawnside, TH-D on the duskside did not observe δE_y oscillation matching the ground Pi2. The δE_y oscillations at TH-D had a period much longer than that observed in the *H* component at HER and in the poloidal magnetic field components at TH-D. Therefore we suggest that the oscillation at TH-D is not a radially trapped fast mode wave.

[23] Frequency domain analysis gives additional details on the frequency dependence of the coherence and cross phase. The waveforms of the compressional component in space and the horizontal component on the ground are compared in Figure 7a. In the waveform plot, TH-A δB_z is enlarged to 150% of the original, and TH-D δB_z is shifted to the left by 9 s to achieve a visual match with δH at the beginning of the event. This time shift incorporates the ~−75° phase delay found in the cross phase spectrum between BOH δH and TH-D δB_z shown in Figure 7d. As shown in Figure 6, the period of TH-D δB_z is longer than those of BOH δH and TH-A δB_z for the first three cycles. The power spectral density, coherence, and cross phase were computed for the 15 min interval from 1930 to 1945 UT using a Fourier transform with five-point smoothing in the frequency domain. The spectral parameters are plotted in Figures 7b, 7c, and 7d. The δB_z data from TH-A and TH-D produce a power spectrum nearly identical to the BOH spectrum in the frequency band from 15 to 20 mHz. In this band the coherence of BOH-TH-A and BOH-TH-D are higher than 0.8.

[24] The cross phases between BOH and TH-D and between BOH and TH-A are about −70° and about 30°, respectively. For an ideal cavity mode wave, two arbitrary points on the same meridian plane will be either 0° or 180°. Because the satellite and ground station were not on the same meridian, azimuthal phase delay could contribute to the observed phase delay. If the phase delay between BOH and TH-D is due to the azimuthal propagation, the pulsation propagates westward, i.e., from BOH (MLT = 3.8) to TH-D (MLT = 18.0), with azimuthal wave number (m) of 0.5. Assuming that the Pi2 source is azimuthally localized near the midnight [*Takahashi and Liou*, 2004], eastward

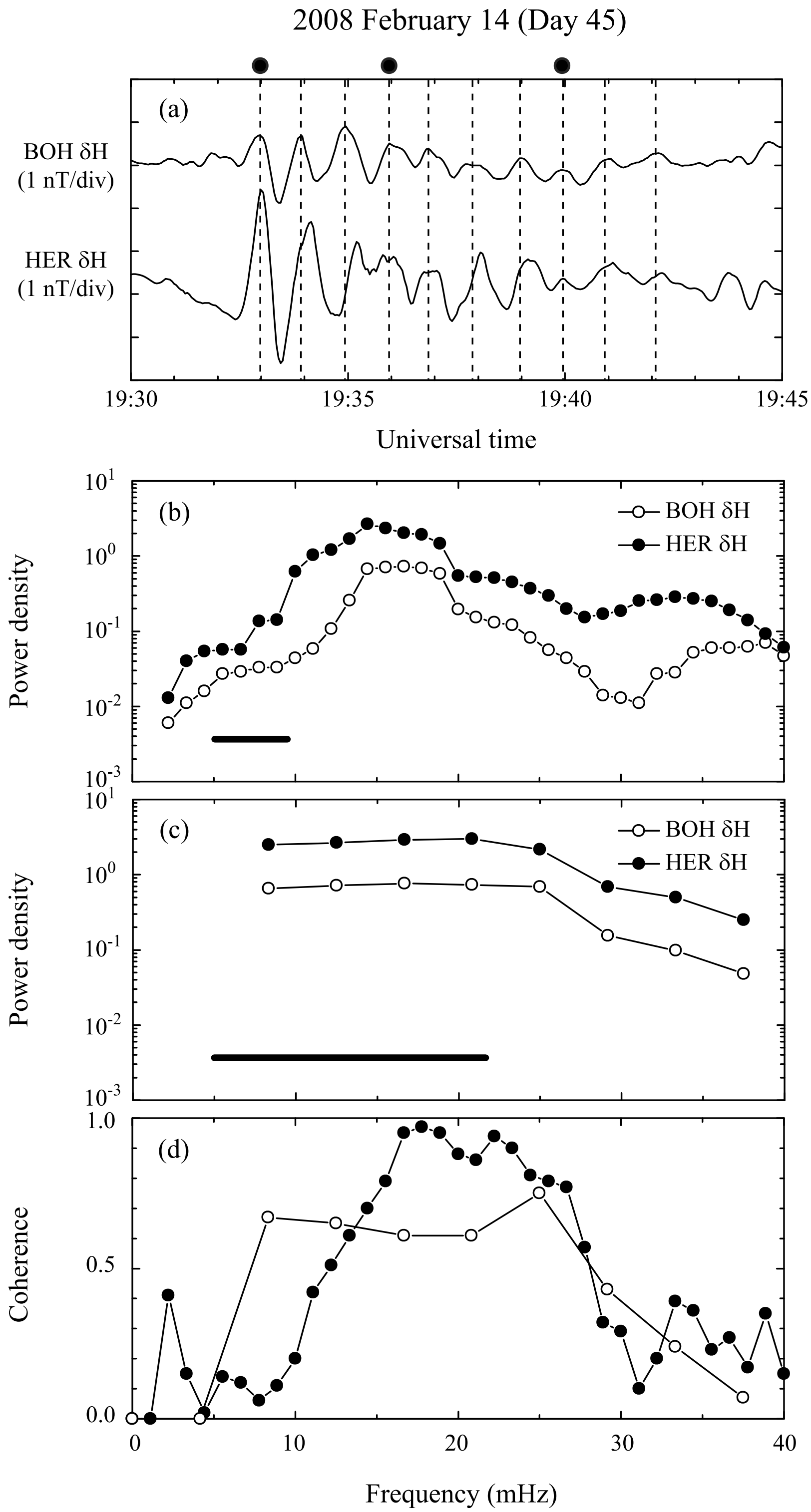

Figure 5. (a) Bohyun (BOH) and Hermanus (HER) *H* components from 1930 to 1945 UT on 14 February 2008. (b) Autopower spectra for BOH δH and HER δH for 1930–1945 UT. (c) Autopower spectra for BOH δH and HER δH for 1932–1936 UT. The horizontal bars are described in the text. (d) The solid (open) circles indicate BOH-HER coherence for 1930–1945 UT (1932–1945 UT).

propagation of Pi2 pulsations in the postmidnight sector is expected. Unlike the expectation, the cross phase between BOH (MLT = 3.8) and TH-A (MLT = 5.3) is about 30°, which is consistent with the TH-E event in the postmidnight sector reported by *Kim et al.* [2010], indicating the westward propagation. Thus, the phase delay between BOH and TH-A cannot be explained by azimuthal propagation away from the source local time.

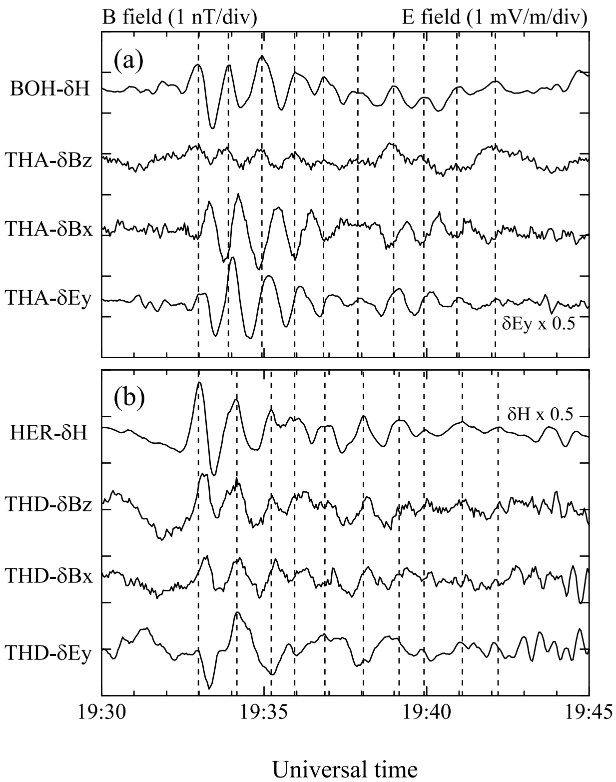

Figure 6. Comparison of (a) TH-A data with Bohyun (BOH) field data and (b) TH-D data with Hermanus (HER) field data.

[25] We examined the waveforms of BOH, TH-A, and TH-E in detail in Figure 8. TH-A was located closely to TH-E. It is confirmed that the oscillations at BOH δH and THEMIS probes δB_z (δB_x) were initially in phase (out of phase) and then the positive (negative) peaks for δB_z (δB_x) slightly lead the peaks of BOH δH over two or three cycles. Such phase delays are also observed in our previous study [see *Kim et al.*, 2010, Figure 4]. These observations indicate that the period of the Pi2 oscillations at BOH, which is located ahead of THEMIS local time in the postmidnight, is slightly longer than that at THEMIS.

3.2. The 16 February 2008 Events

[26] Figure 9a shows the locations of the THEMIS probes and the ground stations at 1923 UT on 16 February 2008. The ground station and THEMIS probe data for a 15 min interval (1915–1930 UT) are plotted in Figures 9b and 9c. Again the THEMIS probes were located near dawn (TH-E: L = 3.1, MLT = 5.0) and dusk (TH-D: L = 2.8, MLT = 17.8). BOH and HER were located in the postmidnight (MLT = 3.6) and premidnight (MLT = 19.9) sectors, respectively. A series of Pi2s starting at ∼1917 UT and at ∼1921 UT were detected at BOH. TH-E also detected corresponding field variations in the poloidal components, δB_x and δE_y. δB_x and δE_y exhibit oscillations with a period identical to that of δH at BOH. δB_x oscillates ∼180° out of phase with δH, and δE_y oscillates nearly in quadrature with BOH δH. These phase delays indicate that the poloidal waves are radially standing, lending support to plasmaspheric resonances (i.e., radially trapped fast mode waves in the plasmasphere). No oscillation with the same period as the Pi2 oscillation starting at ∼1917 UT is seen in the δB_z component, and for the Pi2 oscillation starting at ∼1921 UT, the δB_z component is much smaller than δB_x component, perhaps because TH-E was near the nodal point of the fundamental radial mode of δB_z [*Takahashi et al.*, 1995].

[27] TH-D and HER field data exhibit no similarity to the field oscillations observed by TH-E at dawn and BOH at postmidnight. Although a prominent δH oscillation at HER occurred from 1922 to 1927 UT, its period is clearly longer than that of BOHPi2 in the same time interval. The poloidal magnetic fields around 1925 UT, δB_x and δB_z, at TH-D exhibit oscillations similar to those of the HER δH with a phase delay of ∼90°. The poloidal electric field δE_y oscillated out of phase with the poloidal magnetic fields, indicating that the pulsations at TH-D propagate toward the Earth. The poloidal components at TH-D and the H component at HER do not show any oscillations corresponding to the BOH Pi2 oscillation that occurred around 1917 UT, indicating that the Pi2 pulsation observed in the dawn sector does not exist simultaneously in the dusk sector. As expected from the time series plot of Figure 9, dawn-dusk coherence was very low at the frequency of the peak in the power spectra at BOH δH (data not shown).

[28] The third example occurred on 16 February 2008 at 1057 UT when TH-A was in the afternoon sector (L = 1.8, MLT = 15.4); HER was near noon (MLT = 11.7); and BOH was in the premidnight sector (MLT = 19.4), as shown in Figure 10. The waveforms at TH-A, HER, and BOH are compared in Figure 10b. The H components at BOH and HER are nearly identical and oscillate in phase. At TH-A, however, there are no oscillations in the magnetospheric poloidal field components corresponding to the ground Pi2 signals at HER and BOH. This observation is consistent with that by *Sutcliffe and Lühr* [2010], who searched for evidence of daytime Pi2 in the magnetic field data acquired by the CHAMP satellite at an altitude of ∼400 km. Based on the absence of expected compressional Pi2 signals, they concluded that daytime Pi2s observed on the ground are not compressional oscillations associated with a cavity mode resonance.

3.3. Summary of Selected Pi2 Events

[29] The Pi2 magnetic pulsations observed simultaneously at low-latitude ground stations and by THEMIS probes in the inner magnetosphere have the following characteristics:

[30] 1. Pi2-associated poloidal oscillations observed by THEMIS probes near the dawn and dusk sectors in the inner magnetosphere on 14 February 2008 at 1932 UT and 16 February 2008 at 1921 UT correspond to low-latitude Pi2 pulsations at BOH on the dawnside and at HER on the duskside, respectively. The poloidal oscillations near dawn and dusk have different frequencies. These events are clearly unique in that the different frequencies in the poloidal components are confirmed in space.

[31] 2. The poloidal oscillations on the dawnside showed radially standing fast mode structures. On the duskside, however, the poloidal oscillations do not have such structures. For the 16 February 2008 at 1917 UT case, no poloidal oscillations in the Pi2 frequency band were detected on the duskside.

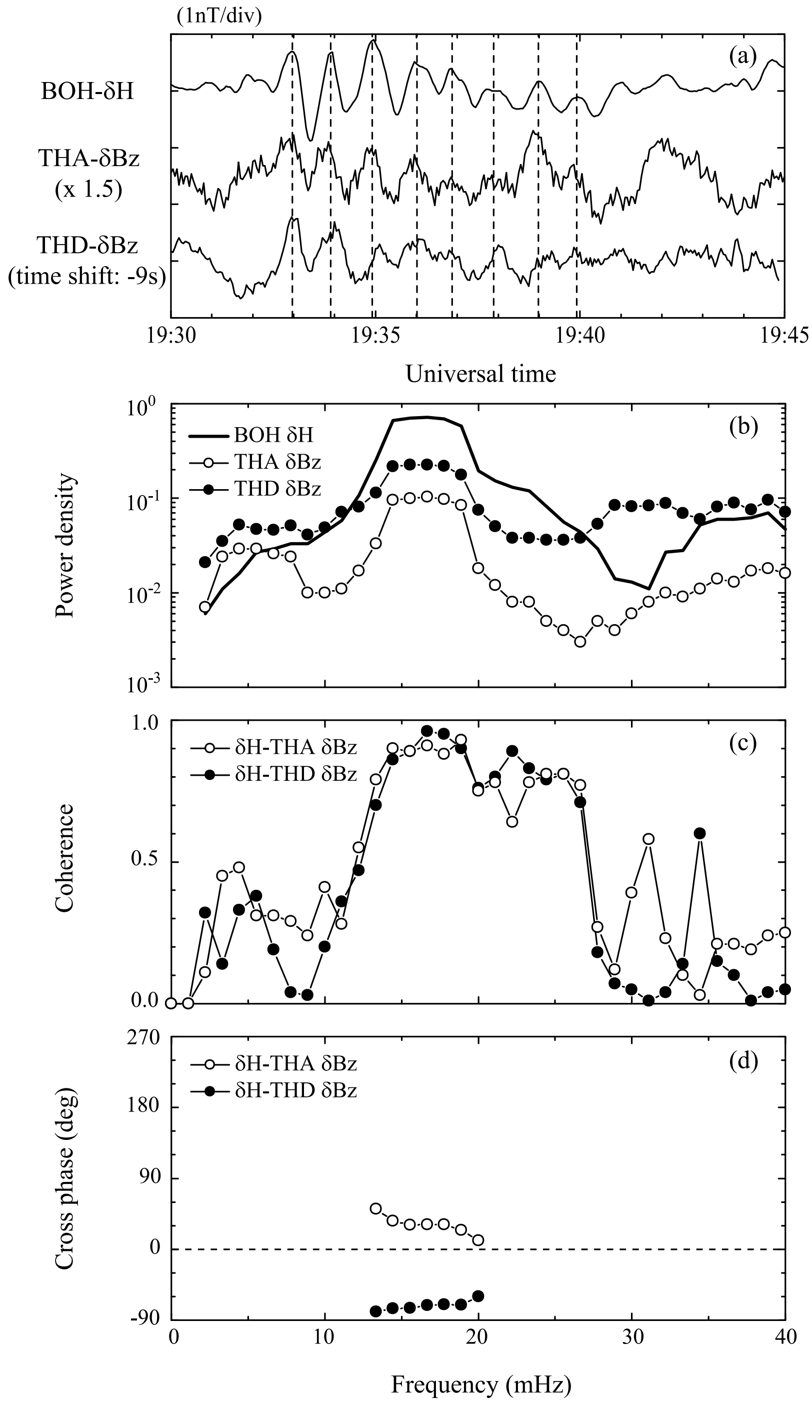

Figure 7. (a) Comparison of BOH δH with the compressional components at TH-A and TH-D. (b) Auto-power spectra for BOH δH and δB_z components at TH-A and TH-D. (c) Coherence. (d) Cross phase.

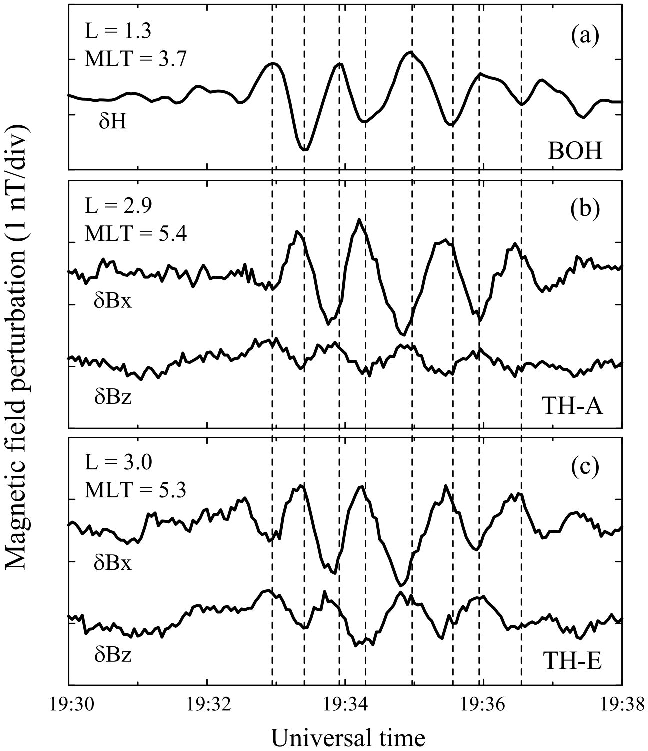

Figure 8. Magnetic field perturbations at (a) BOH, (b) TH-A, and (c) TH-E. The vertical dashed lines indicate the positive and negative peaks at BOH *H* component.

[32] 3. The dayside low-latitude Pi2 is not associated with a fast mode wave propagating to the dayside through the magnetosphere.

4. Statistical Analysis

[33] In this section we present a statistical analysis of the 48 Pi2 events identified at BOH. To determine wave mode structure (i.e., radially standing or propagating), we need multipoint observations of the spatial variations of the magnetic and electric field perturbations from at least one probe providing evidence of compressional magnetic field oscillation in the magnetosphere. Thus, we focus on the poloidal components at THEMIS probes.

[34] Figure 11a shows the local time distribution of the 48 Pi2 events at BOH. The occurrence of events at BOH is heavily biased to the postmidnight sector. This local time dependence is due to limitations in THEMIS probe locations (see Figure 3). In our study, we selected BOH Pi2 events from time intervals during which at least one THEMIS probe was at $L < 4$ and $0400 \le \mathrm{MLT} \le 20.0$. Since the probes had orbital periods close to 24 h, this meant that BOH observations were made in a limited UT (thus MLT) interval. Figure 11b shows the distribution of the THEMIS MLT for the Pi2 events identified at BOH.

[35] We examined the coherence between BOH δH and the poloidal components at THEMIS probes. In our study, high coherence means that the *H* component at BOH and one of the poloidal components at THEMIS probes have spectral peaks at the same frequency, and at this frequency the coherence is higher than 0.6. As shown in the case study, we note that high-coherence values (>0.6) cannot always ensure that identical waves are excited at spatially separated locations. The distribution of high-coherence BOH-THEMIS events is plotted in Figure 11 using black shadings. Although the distribution of high-coherence events at THEMIS probes

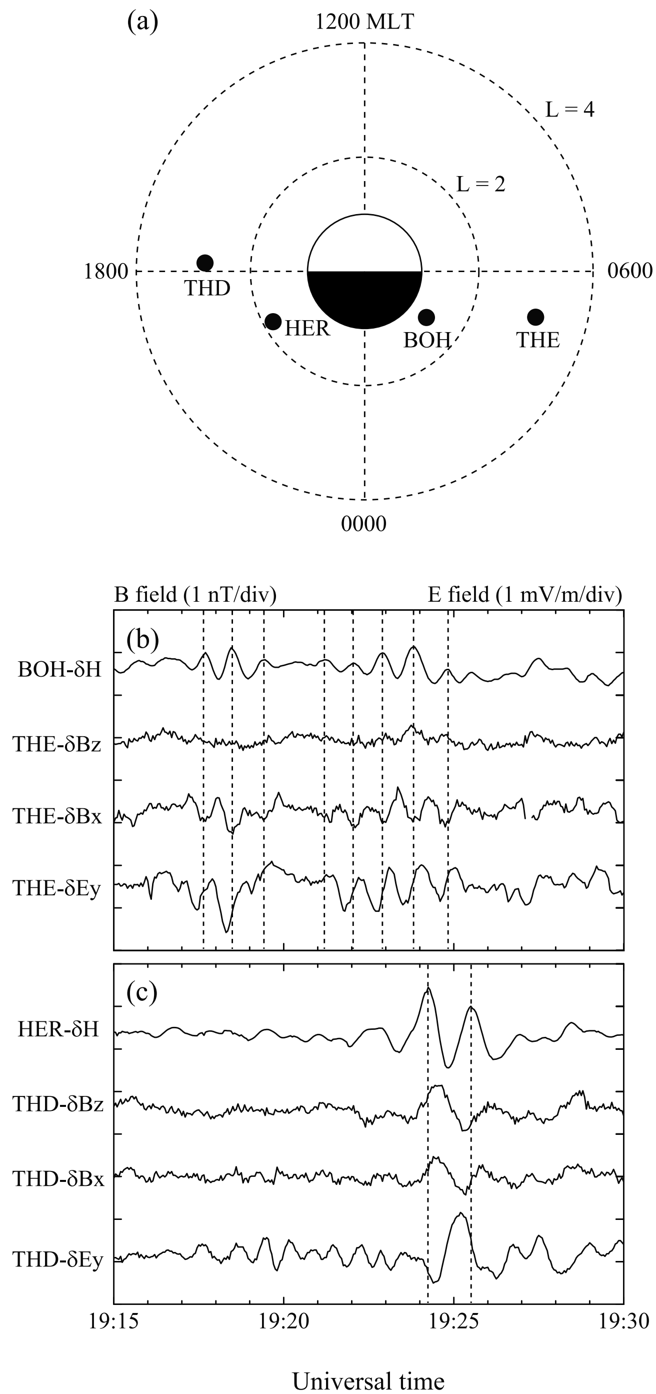

Figure 9. (a) Location of THEMIS probes and ground stations in the *L*-MLT plane at 1921 UT on 16 February 2008. (b) Bohyun and TH-E and (c) Hermanus and TH-D data from 1915 to 1930 UT on 16 February 2008.

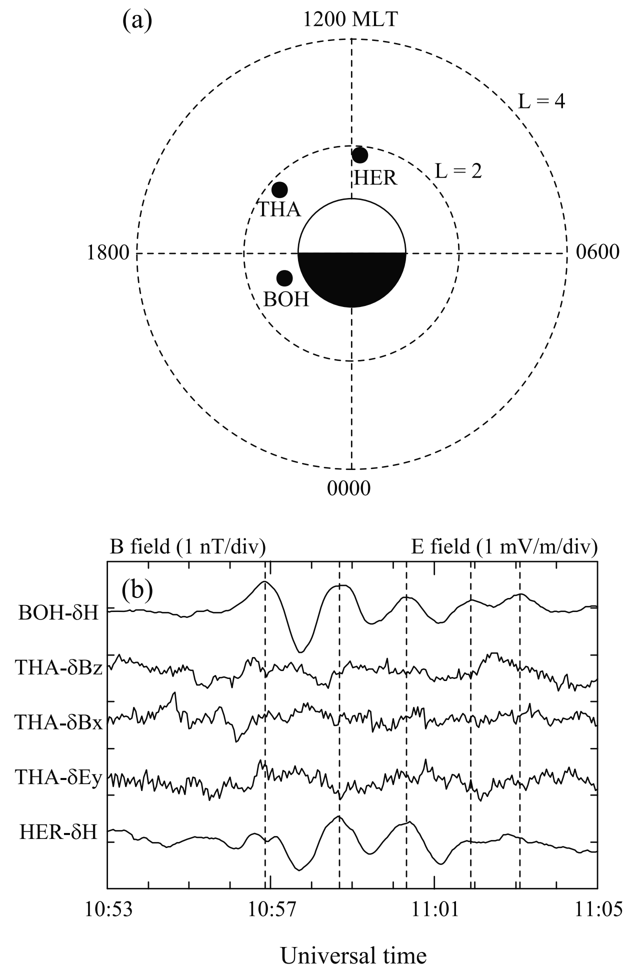

Figure 10. (a) Location of THEMIS probes and ground stations in the L-MLT plane at 1056 UT on 16 February 2008. (b) Bohyun, TH-A, and Hermanus data from 1053 to 1105 UT on 16 February 2008.

is skewed near dawn, some were observed in the morningside (MLT = 6.0–8.0), extending the transition region between nightside and dayside. There are no high-coherence events at 9.0–18.0 MLT. This is consistent with the results of *Takahashi et al.* [1995] and *Sutcliffe and Lühr* [2010]. There were very few high-coherence events on the duskside.

[36] Figure 12 shows the local time distribution of the Pi2 events at BOH and HER, sorted according to the degree of coherence between these stations. Because HER is located west of BOH by ~8 h, Pi2 events at HER are distributed primarily in MLT = 15.0–2.00. Unlike THEMIS probes, HER detected events at MLT = 11.0–18.0 that show high coherence with the nightside BOH events. From the comparison of local time distributions of BOH-THEMIS and BOH-HER high-coherence events, we suggest that the daytime Pi2 observed on the ground is not a pulsation propagating through the magnetosphere from nightside to dayside.

[37] As shown in Figure 11, the Pi2 pulsations at BOH and the corresponding poloidal pulsations at THEMIS are localized in longitude. To quantify the longitudinal range of the signal propagation, the occurrence rate of high-coherence BOH-THEMIS events is plotted as a function of the local time separation (|ΔMLT|) between BOH and THEMIS in Figure 13. The majority of high-coherence events appear at |ΔMLT| < 3. When |ΔMLT| was larger than 5 h, the occurrence rate of high-coherence events dramatically decreases. From these results, we suggest that there is strong longitudinal attenuation of the fast mode wave as it propagates azimuthally from a source region localized in longitude.

[38] Figure 14 shows the cross phase among the poloidal components at THEMIS probes for the high-coherence events. The horizontal dashed lines at 180° and 0° in Figure 14a indicate the radial phase structure between δB_z and δB_x for the ideal fundamental cavity mode in the Southern Hemisphere and the Northern Hemisphere, respectively, inward of a δB_z nodal point [*Takahashi et al.*, 1995]. Note that the cross phase switches across the nodal point of δB_z. At $L < 3.3$ the δB_z and δB_x cross phase values from the Southern (MLAT < 0) Hemisphere stay near 180°, and one data point from the Northern (MLAT > 0) Hemisphere lies near 0°. The observed cross phase is consistent with the cavity mode. One data point from the Southern Hemisphere lies near 0° at $L = \sim 3.4$. If this event is observed beyond the δB_z nodal point, the cross phase also fits the cavity mode. Figure 14b shows the δB_z and δE_y cross phase.

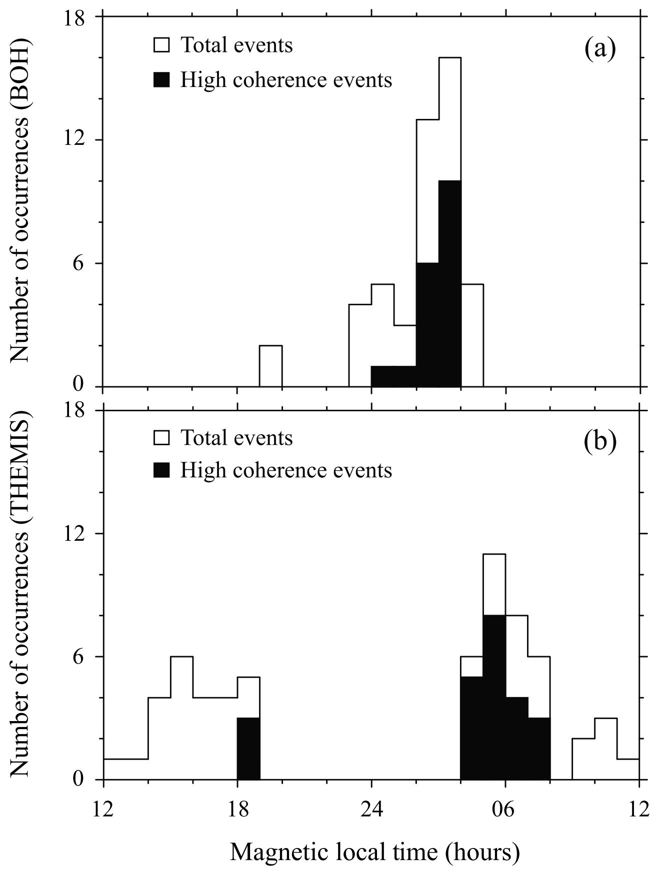

Figure 11. (a) The local time occurrence distribution of the 48 Pi2 events identified at BOH. (b) The distribution of the THEMIS probe locations in MLT when a Pi2 event was identified at BOH. The distribution of the high-coherence BOH-THEMIS events is indicated by black shading.

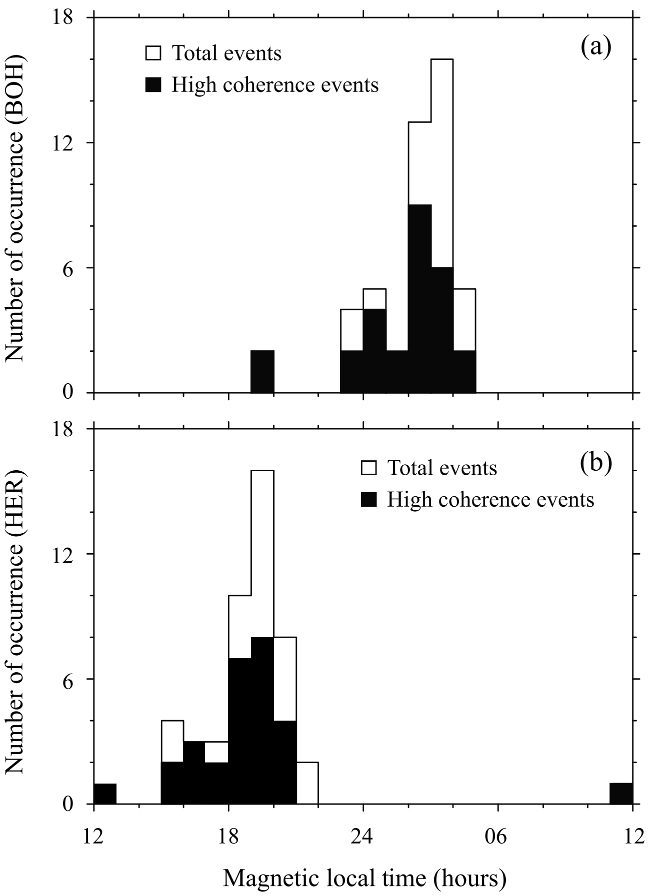

Figure 12. Occurrence distribution for MLT of Pi2 events based on (a) Bohyun and (b) Hermanus observations. The format is the same as in Figure 11.

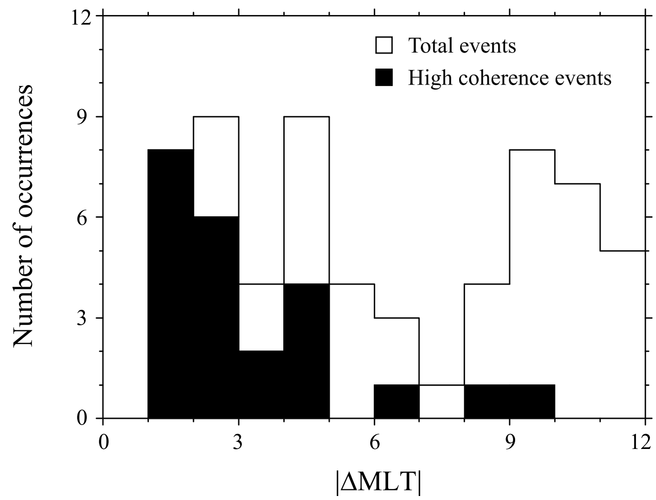

Figure 13. Occurrence distribution of Pi2 events as a function of the magnetic local time separation between THEMIS probes and Bohyun (|ΔMLT|).

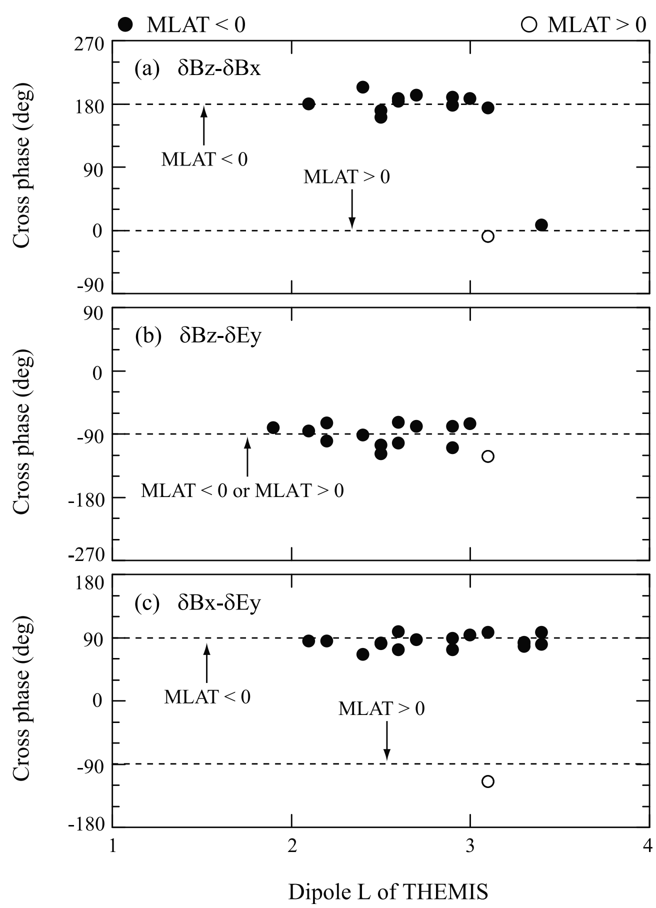

Figure 14. Cross phase between (a) δB_z and δB_x components, (b) δB_z and δE_y components, and (c) δB_x and δE_y components at THEMIS probes for the high ground probe coherence events. The solid (open) circles indicate observation in the Southern (Northern) Hemisphere. The horizontal dashed lines indicate the radial mode structure for the ideal fundamental cavity mode.

The phase values are close to −90° regardless of MLAT and radial distance, as expected for the cavity mode [*Takahashi et al.*, 2001]. The δB_x and δE_y cross-phase values from the Southern and Northern Hemispheres remain near 90° and −90°, respectively (Figure 14c). These radial phase structures are also consistent with the cavity mode.

[39] Figure 15 shows the BOH-THEMIS cross phase as a function of L. The relative phase values are clustered near the radial phase profile expected from the cavity mode. Compared with the cross phases among the poloidal components at THEMIS probes plotted in Figure 14, the BOH-THEMIS cross phase values are more scattered about the theoretical value. This is may be due to the longitudinal separation between BOH and THEMIS probes. Positive phase delays of $\delta H - \delta B_z$ indicate that the wave propagates from THEMIS to BOH. Note that for all events in Figure 15, BOH was located ahead of THEMIS local time in the postmidnight. Thus, the positive phase delay is not due to the westward propagation of Pi2 pulsations because Pi2's source near the midnight is close to BOH rather than THEMIS. We showed that the positive phase delay is due to slightly different Pi2 frequencies at BOH and THEMIS in Figure 8. We examined visually the time series of BOH and THEMIS data for 15 high-coherence $\delta H - \delta B_z$ events in Figure 15 and found five events showing that the period at BOH is slightly longer than that at THEMIS, such as the example shown in Figure 8.

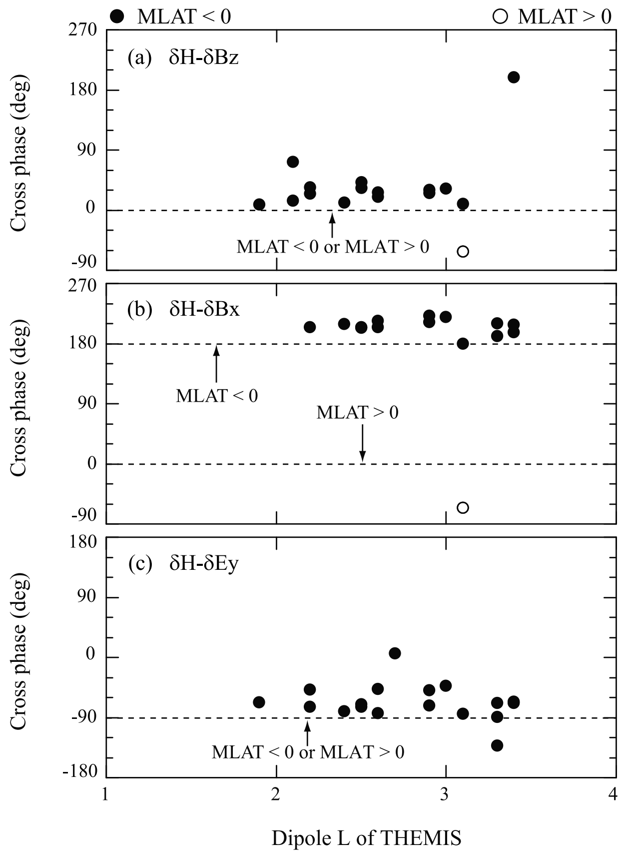

Figure 15. Cross phase between (a) δB_z and H components, (b) δB_x and H components, and (c) δB_x and H components for the high ground probe coherence events. The format is the same as in Figure 14.

Thus, some part of the positive phase delay may be due to longitudinally different frequencies. However, we do not exclude a possibility that the observed phase delay is associated with a phase delay of fast mode waves transmitted through the ionosphere [*Takahashi et al.*, 1999].

[40] Figure 16a shows dynamic spectrum for the BOH *H* component on 16 February 2008. On the top of the spectrum, the 3 h values of the *Kp* index are displayed. The spectrum is obtained by using a moving-time window Fourier transform method [*Bendat and Piersol*, 2010] with a window length of 240 points (20 min). The window moves forward by 60 data points in successive steps. Seven point averages are taken over frequency to smooth the spectral parameters. Intermittent Pi2 band (~6–25 mHz) oscillations are evident when BOH was on the nightside from ~2000 to ~0600 LT, and their power levels are strongly time-modulated. A major feature evident in the spectrogram is the local time dependence of the frequency in the Pi2 band, i.e., a gradual increase in frequency from evening (~2000 LT) to morning (~0600 LT), consistent with previous observations [*Han et al.*, 2003; *Takahashi and Liou*, 2004]. This structure may be due to temporal and spatial variations of the plasmapause location along the longitude. To minimize the temporal effect and examine the spatial variation of the Pi2-frequency change, average spectrum is calculated from all spectral data (i.e., 29 one day dynamic spectra) in February 2008 and plotted in Figure 16b with the average *Kp* values. The average spectrum also shows a continuous structure that consists of frequencies smoothly increasing from premidnight to postmidnight. Since the average 3 h *Kp* values are about 2, the local time dependence of Pi2 frequencies can be attributed to the spatial effect. That is, the averaged plasmapause distance is smaller on the dawnside than near the midnight. From 1800 to 2000 LT, pulsation power is not evident in the

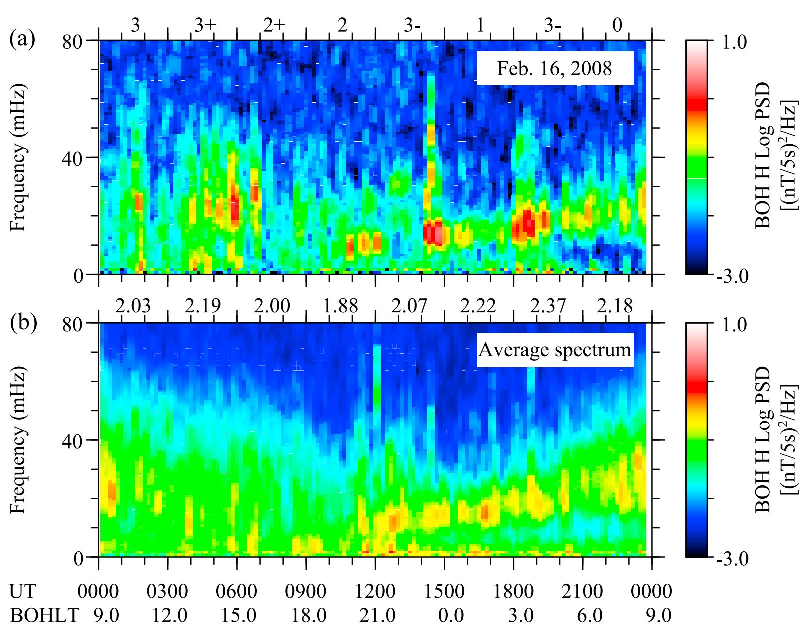

Figure 16. (a) Dynamic power spectrum for the BOH *H* component on 16 February 2008. The data were time differenced prior to spectral estimate to remove a slowly varying background. (b) Average spectrum for 29 one day dynamic spectra in February 2008. The 3 h values of the *Kp* index and the average 3 h *Kp* values are displayed on the top of each spectrum. Universal time and the local time of BOH (BOHLT) are shown at the bottom.

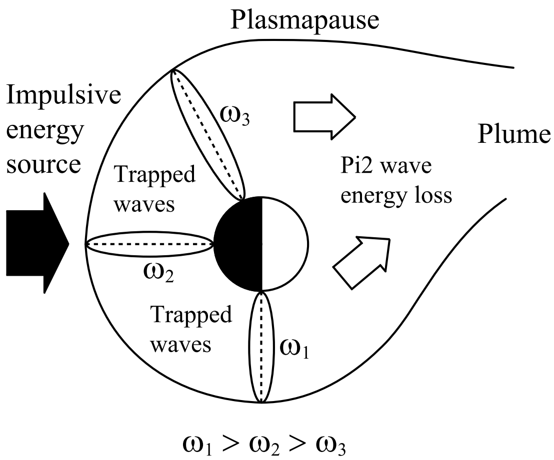

Figure 17. Trapped fast mode waves in a longitudinally nonuniform plasmasphere. The ω_1, ω_2, and ω_3 indicate two-dimensional mode frequencies confined to the meridional plane near dawn, midnight, and premidnight, respectively.

6 to 25 mHz band. This may be due to the fact that Pi2 wave energy is not well trapped in that local time region.

5. Discussion

[41] Plasmaspheric resonance in the nightside inner magnetosphere is a strong candidate for a low-latitude Pi2 pulsation mechanism [e.g., *Takahashi et al.*, 1995, 2001, 2003; *Nosé*, 2010]. Until now, however, little attention has been paid to Pi2-associated fast mode waves near dawn and dusk in the inner magnetosphere. We presented case studies with statistical analysis to get insight into the spatial variation of fast mode wave properties near the transition regions between nightside and dayside.

[42] Longitudinally separated multipoint observations in the inner magnetosphere provide new information on the local time dependence of Pi2 characteristics. The 14 February 2008 event presented in section 3.1 showed that Pi2 frequency varies with longitude, both in space and on the ground. This frequency is higher near dawn than near dusk. The Pi2-associated poloidal oscillation near dawn was observed as a radially trapped fast mode wave, (i.e., a radially standing wave mode). The mode structure of the pulsation near dusk was not clear, however. Two Pi2 pulsations presented in section 3.2 occurred in succession at 1917 and 1921 UT on 16 February 2008. Near dawn both Pi2 events also show radially trapped standing mode structure. No poloidal oscillations corresponding to the 1917 UT event were detected near dusk, however. Similar observations have been reported by *Kim et al.* [2010] using THEMIS probe data in the inner magnetosphere. During the 1921 UT event, oscillations in the poloidal components were detected near dusk. They were not a radially standing mode, however. The frequency of the 1921 UT event is lower near dusk than near dawn. From these observational results we suggest that well-defined radially standing fast mode waves are easily excited near dawn but not near dusk, and that the frequency of the radially trapped fast mode wave is higher near dawn than near dusk if the waves are excited simultaneously at both locations. These suggestions can be confirmed in the average dynamic spectrum of the BOH *H* component plotted in Figure 16b.

[43] The frequency of the plasmaspheric cavity mode oscillation is determined by the size of the plasmasphere and the Alfvén speed. Thus, a local time-dependent frequency can be expected in an asymmetric plasmasphere. *Fujita and Itonaga* [2003] examined power spectra of a plasmaspheric resonance with a longitudinally asymmetric Alfvén speed (larger in the dawnside and smaller in the duskside), which is equivalent to larger plasmapause distance in the dusk sector than in the dawn sector, and found that the dominant frequency of the plasmaspheric resonance is higher at dawn than at dusk. If Pi2 wave energy is conserved inside the plasmasphere, an approximate plasmaspheric resonance frequency is given by

$$\omega_{lmn} = \pi\left[(l/L_x)^2 + (m/L_y)^2 + (n/L_z)^2\right]^{1/2} \bar{V}_A \qquad (1)$$

where L_x, L_y, and L_z are radial, azimuthal, and north-south length scales, respectively; l, m, and n are quantum numbers in each direction; and $\bar{V}_A$ is the effective Alfvén speed [*Lee*, 1996]. From (1) it is expected that plasmaspheric resonance consists of many harmonics having different sets of frequency. In a dipole-like system the azimuthal scale size is larger than the radial and north-south length scales, which determine meridional mode structure in the plasmasphere, so the plasmaspheric resonance frequency is less affected by different azimuthal wave numbers. Furthermore the azimuthal mode structure may take a longer time to develop than the meridional mode structure. If Pi2 wave energy is lost as the wave propagates azimuthally from nightside to dayside [*Takahashi et al.*, 1995], the plasmaspheric resonance may not fully establish quantized mode structures. That is, the plasmaspheric resonance may not be established as a common frequency observed at all local times but instead may be generated as a two-dimensional mode confined to the meridional plane as illustrated in Figure 17. In a longitudinally nonuniform plasmasphere [e.g., *Goldstein et al.*, 2005], plasmaspheric resonance frequency may change with longitude. There is loss of wave energy from plume region. As shown in the average dynamic spectrum of BOH *H* of Figure 16, the continuous frequency change in the Pi2 frequency band indicates that the averaged plasmapause distance is longitudinally nonuniform.

[44] Some BOH-THEMIS high-coherence events were even observed when THEMIS probes were in the morning sector (MLT = 6.0–8.0), as shown in Figure 11. *Nośe et al.* [2003] also reported a Pi2 pulsation observed at the ETS-VI satellite in the morningside plasmasphere. The morningside Pi2 has the same period as low-latitude Pi2 on the nightside, and it has been regarded as cavity mode resonance. From these observations we suggest that Pi2 wave energy is well conserved as it propagates toward the morning sector but not so toward the afternoon sector. That is, longitudinal loss of Pi2 wave energy is larger on the duskside than on the dawnside, perhaps because duskside plasmapause shape (e.g., the plasmaspheric drainage plume) is more complicated than dawnside plasmapause shape.

[45] Comparing Figures 14 and 15, we suggest that the phase deviation from the ideal cavity mode could be related to energy loss from the plasmaspheric cavity. As shown in Figure 13, high-coherence events were observed when THEMIS probes and BOH were close to each other. This suggests that wave energy escaped azimuthally. Although Pi2 pulsations occur simultaneously both on the nightside and dayside at low-latitude ground stations [*Sutcliffe and Yumoto*, 1989, 1991], spacecraft data provide no evidence of Pi2 pulsations on the dayside in the inner magnetosphere [*Takahashi et al.*, 1995; *Sutcliffe and Lühr*, 2010]. That is, there is no indication that Pi2 pulsations propagate to the dayside in a compressional mode. The absence of the compressional Pi2 pulsation may also be interpreted as longitudinal attenuation of fast mode waves in the magnetosphere.

[46] *Han et al.* [2004] reported two daytime Pi2 events in space. Both were observed near MLT = 14.0–15.0 at ∼600–700 km in altitude and oscillated in antiphase to low-latitude ground Pi2s on the dayside or nightside. *Han et al.* [2004] suggested that daytime Pi2s are not due to a global cavity mode resonance but are caused by currents flowing in the ionosphere. The 1957 UT event on 16 February 2008 (see Figure 10) clearly shows that the daytime Pi2 at HER is not a fast mode wave propagating to the dayside through the magnetosphere. As suggested by *Han et al.* [2004] and *Sutcliffe and Lühr* [2010], the daytime HER Pi2s may be associated with currents flowing in the ionosphere.

6. Conclusions

[47] We have studied the properties of Pi2 pulsations observed by THEMIS probes in the inner magnetosphere and at low-latitude ground stations. When on the dawnside, THEMIS probes detected poloidal oscillations corresponding to low-latitude Pi2 pulsation in postmidnight and exhibiting properties of radially standing fast waves consistent with plasmaspheric resonance. When on the duskside, however, probes did not detect the resonance signature. This local time dependence of the Pi2 pulsation property could be explained by nonuniform plasmapause shape (i.e., smooth dawnside plasmapause and structured duskside plasmapause). Thus, we suggest that longitudinal loss of Pi2 wave energy is larger on the duskside than on the dawnside. Because of the azimuthal loss of wave energy, the plasmaspheric resonance may be established as a two-dimensional standing mode structure localized in longitude. The longitudinal decay in amplitude of the fast mode wave leads to the lack of high coherence between dayside probe data and nightside low-latitude data. Thus, the daytime low-latitude Pi2s are not associated with fast mode waves excited by plasmaspheric resonance.

[48] **Acknowledgments.** The geomagnetic *AL* index was provided by World Data Center C2 (WDC-C2) for Geomagnetism, Kyoto University. The Bohyun magnetic field data were provided by the Solar and Space Weather Research Group in Korea Astronomy and Space Science Institute. This work was supported by the WCU program through NRF funded by MEST of Korea (R31-10016). Work of K.-H. Kim was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011–0004090) and also supported by KASI grant. Work at JHU/APL was supported by NSF grant ATM-0750689.

[49] Robert Lysak thanks Kazuo Shiokawa and the other reviewers for their assistance in evaluating this paper.

References

Allan, W., S. P. White, and E. M. Poulter (1986), Impulse-excited hydromagnetic cavity and field-line resonances in the magnetosphere, *Planet. Space Sci.*, *34*, 371.

Auster, H. U., et al. (2008), The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, *141*, 235, doi:10.1007/s11214-008-9365-9.

Bendat, J. S., and A. G. Piersol (2010), *Random Data: Analysis and Measurement Procedures*, 604 pp., John Wiley, New York.

Bonnell, J. W., F. S. Mozer, G. T. Delory, A. J. Hull, R. E. Ergun, C. M. Cully, V. Angelopoulos, and P. R. Harvey (2008), The Electric Field Instrument (EFI) for THEMIS, *Space Sci. Rev.*, *141*, 303, doi:10.1007/s11214-008-9469-2.

Clauer, C. R., and R. L. McPherron (1974), Mapping the local time–universal time development of magnetospheric substorms using mid-latitude magnetic observations, *J. Geophys. Res.*, *79*, 2811.

Fujita, S., and M. Itonaga (2003), A plasmaspheric cavity resonance in a longitudinally non-uniform plasmasphere, *Earth Planets Space*, *55*, 219.

Goldstein, J., J. L. Burch, B. R. Sandel, S. M. Mende, P. C. Brandt, and M. R. Hairston (2005), Coupled response of the inner magnetosphere and ionosphere on 17 April 2002, *J. Geophys. Res.*, *110*, A03205, doi:10.1029/2004JA010712.

Han, D., T. Iyemori, Y. Gao, Y. Sano, F. Yang, W. Li, and M. Nosé (2003), Local time dependence of the frequency of Pi2 waves simultaneously observed at 5 low-latitude stations, *Earth Planets Space*, *55*, 601.

Han, D.-S., T. Iyemori, M. Nosé, H. McCreadie, Y. Gao, F. Yang, S. Yamashita, and P. Stauning (2004), A comparative analysis of low-latitude Pi2 pulsations observed by Ørsted and ground stations, *J. Geophys. Res.*, *109*, A12303, doi:10.1029/2004JA010597.

Kim, K.-H., and K. Takahashi (1999), Statistical analysis of compressional Pc3.4 pulsations observed by AMPTE CCE at L = 2.3 in the dayside magnetosphere, *J. Geophys. Res.*, *104*, 4539.

Kim, K.-H., H.-J. Kwon, D.-H. Lee, H. Jin, K. Takahashi, V. Angelopoulos, J. W. Bonnell, K. H. Glassmeier, Y.-D. Park, and P. Sutcliffe (2010), A comparison of THEMIS Pi2 observations near the dawn and dusk sectors in the inner magnetosphere, *J. Geophys. Res.*, *115*, A12226, doi:10.1029/2010JA016010.

Kosaka, K., T. Iyemori, M. Nosé, M. Bitterly, and J. Bitterly (2002), Local time dependence of the dominant frequency of Pi2 pulsations at mid- and low-latitudes, *Earth Planets Space*, *54*, 771.

Lee, D.-H. (1996), Dynamics of MHD wave propagation in the low-latitude magnetosphere, *J. Geophys. Res.*, *101*, 15,371.

Nosé, M. (2010), Excitation mechanism of low-latitude Pi2 pulsations: Cavity mode resonance or BBF-driven process?, *J. Geophys. Res.*, *115*, A07221, doi:10.1029/2009JA015205.

Nosé, M., et al. (2003), Multipoint observations of a Pi2 pulsation on morningside: The 20 September 1995 event, *J. Geophys. Res.*, *108*(A5), 1219, doi:10.1029/2002JA009747.

Saito, T. (1969), Geomagnetic pulsations, *Space Sci. Rev.*, *10*, 319.

Sibeck, D. G., and V. Angelopoulos (2008), THEMIS science objectives and mission phases, *Space Sci. Rev.*, *141*, 35, doi:10.1007/s11214-008-9393-5.

Sutcliffe, P. R., and H. Lühr (2010), A search for dayside geomagnetic Pi2 pulsations in the CHAMP low-Earth-orbit data, *J. Geophys. Res.*, *115*, A05205, doi:10.1029/2009JA014757.

Sutcliffe, P. R., and K. Yumoto (1989), Dayside Pi2 pulsations at low latitudes, *Geophys. Res. Lett.*, *16*, 887.

Sutcliffe, P. R., and K. Yumoto (1991), On the cavity mode nature of low-latitude Pi2 pulsations, *J. Geophys. Res.*, *96*, 1543.

Takahashi, K., and K. Liou (2004), Longitudinal structure of low-latitude Pi2 pulsations and its dependence on aurora, *J. Geophys. Res.*, *109*, A12206, doi:10.1029/2004JA010580.

Takahashi, K., S. Ohtani, and B. J. Anderson (1995), Statistical analysis of Pi2 pulsations observed by the AMPTE CCE spacecraft in the inner magnetosphere, *J. Geophys. Res.*, *100*, 21,929.

Takahashi, K., B. J. Anderson, and K. Yumoto (1999), Upper atmosphere research satellite observation of a Pi2 pulsation, *J. Geophys. Res.*, *104*, 25,035.

Takahashi, K., S.-I. Ohtani, W. J. Hughes, and R. R. Anderson (2001), CRRES observation of Pi2 pulsations: Wave mode inside and outside the plasmasphere, *J. Geophys. Res.*, *106*, 15,567.

Takahashi, K., D.-H. Lee, M. Nosé, R. R. Anderson, and W. J. Hughes (2003), CRRES electric field study of the radial mode structure of Pi2 pulsations, *J. Geophys. Res.*, *108*(A5), 1210, doi:10.1029/2002JA009761.

Yeoman, T. K., and D. Orr (1989), Phase and spectral power of mid-latitude Pi 2 pulsations: Evidence for a plasmaspheric cavity resonance, *Planet. Space Sci.*, *37*, 1367.

Zhu, X., and M. G. Kivelson (1989), Global mode ULF pulsations in a magnetosphere with a nonmonotonic Alfvén velocity profile, *J. Geophys. Res.*, *94*, 1479.

V. Angelopoulos, IGPP, University of California, Los Angeles, CA 90095-1565, USA.

H. U. Auster, IGEP, Technical University of Braunschweig, Mendelssohnstrasse 3, D-38106 Braunschweig, Germany.

H. Jin, K.-H. Kim, H.-J. Kwon, D.-H. Lee, and E. Lee, School of Space Research, Kyung Hee University, 1 Seocheon-dong, Giheung-gu, Yongin-si, Gyeonggi-do, 446-701, South Korea. (khan@khu.ac.kr)

J. Lee and Y.-D. Park, Korea Astronomy and Space Science Institute, Whaam-Dong, Youseong-gu, Daejeon, 305-348, South Korea.

P. R. Sutcliffe, South African National Space Agency Space Science, PO Box 32, Hermanus 7200, South Africa.

K. Takahashi, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723-6099, USA.