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# Pi2 pulsations in a small plasmasphere

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**Abstract.** We study a Pi2 pulsation occurred at ∼1520 UT on August 29, 2000. This Pi2 event was observed at ground stations from high (geomagnetic latitude = ∼65°) to low latitudes (∼17°) near midnight with an identical waveform and oscillated with a frequency of ∼11 mHz. During the event the global plasmaspheric structure was obtained from the IMAGE satellite and the location of the plasmapasue was clearly identified. The plasmasphere was asymmetric and the plasmapause was located at $L \sim 3$ (2) near the dawnside (duskside). Using a magnetospheric mass density model constructed from the IMAGE satellite data [*Denton et al.*, 2005], we examine whether the Pi2 pulsation observed inside the plasmapause can be explained by a plasmaspheric cavity mode. We find that the 11-mHz oscillation is too low to be established as a cavity mode in the plasmasphere. Thus, the plasmaspheric cavity mode is not an appropriate model for the Pi2 pulsation at mid and low latitudes. The Pi2 pulsation was observed at high latitude outside the plasmapause with nearly identical frequency at low latitude. We discuss what determines its period and waveform.

## 1. Introduction

Pi2 magnetic pulsations in the period range from 40 to 150 s are transient and irregular geomagnetic oscillations. They are commonly observed from high latitude in the auroral zone to the magnetic equator on the nightside at the onset of magnetospheric substorms [*Saito*, 1969], but different models for different latitudes have been proposed [*Olson*, 1999]. Since Pi2 pulsation occurs at a substorm onset, it is believed that its energy is released as the magnetic field of the near-Earth magnetotail suddenly changes from a tail-like configuration to a dipole-like configuration. However, it is not completely understood how and where Pi2 pulsation establishes as a regular oscillation and what determines its period.

Pi2 pulsation at auroral latitude has been interpreted as transient Alfvén waves [*Baumjohann and Glassmeier*, 1984; *Bauer et al.*, 1995]. The wave period is determined by the Alfvén travel time between the auroral ionosphere and the neutral sheet. The transient Alfvén waves are associated with the field-aligned currents, which produce additional ground perturbations on east-west component at mid latitude, diverted from the cross-tail current. Since the polarization pattern of Pi2 pulsations at mid latitude varies systematically relative to the center of the substorm current wedge (SCW) [*Lester et al.*, 1983], SCW model is favored for a generation mechanism of mid-latitude Pi2 pulsations. Shear Alfvén mode resonances [*Fukunishi*, 1975], surface waves on the plasmapause [*Sutcliffe*, 1975], and cavity mode resonances [*Saito and Matsushita*, 1968] have been proposed as generation mechanisms of Pi2 pulsations at mid and low latitudes where the field lines are within the plasmapause.

Ground-based observations [e.g., *Stuart*, 1974; *Yeoman and Orr*, 1989; *Lin et al.*, 1991; *Takahashi and Liou*, 2004] and satellite observations [e.g., *Takahashi et al.*, 1995; *Takahashi et al.*, 2001; *Kim et al.*, 2001; *Keiling et al.*, 2001; *Han et al.*, 2004] showed that the cavity mode is a promising mechanism for Pi2 pulsations in the inner magnetosphere ($L < 4$-5). A number of theoretical model calculations showed that a well-defined cavity mode can be established in the plasmasphere [*Fujita and Glassmeier*, 1995; *Fujita et al.*, 2002; *Lee*, 1996, 1998; *Lee and Kim*, 1999; *Lee and Lysak*, 1999]. Recently, *Takahashi et al.* [2003] found a negative correlation between the Pi2 frequency at low latitude and the distance of the plasmapause and attributed it to the evidence of the plasmaspheric cavity mode.

There is a competing model for low-latitude Pi2 pulsations, which is the driven Pi2 mechanism. *Kepko and Kivelson* [1999] and *Kepko et al.* [2001] showed that low-latitude Pi2 pulsations can be directly driven by bursty bulk flows (BBFs) in the near-Earth magnetotail and suggested that BBFs in the magnetotail determine the properties of the low-latitude Pi2 pulsations. *Shiokawa et al.* [1998] reported that Pi2 pulsations in the plasmasphere can be generated by compressional pulses produced by high-speed earthward flows in the near tail. *Osaki et al.* [1998], who observed Pi2 pulsations off the magnetic equator in the plasmasphere, suggested that the Pi2 pulsations are not a simple cavity mode oscillation excited by an impulsive source but due to a quasi-periodic source external to the plasmasphere.

In this paper we focus on a Pi2 pulsation occurred at ∼1520 UT on August 29, 2000. During the event the spatial structure of the plasmasphere was obtained by the IMAGE satellite and the plasmapause was well defined. Using mulipoint ground-based data and a realistic magnetospheric mass density model [*Denton et al.*, 2005], we examine a generation mechanism of the Pi2 pulsation observed at low latitude.

The organization of the paper is as follows. In section 2 we briefly describe the data sets used in this study. In section 3 we describe the data analysis. In section 4 we discuss whether the observed Pi2 pulsations are generated by the plasmaspheric cavity mode resonance or driven by oscillating sources outside the plasmapause. Section 5 gives conclusions.

## 2. Data Sets

The data used in this study were acquired by ground-based magnetometers. They were obtained from the Circum-pan Pacific Magnetometer Network (CPMN) [*Yumoto et al.*, 1996], the Sino Magnetic Array at Low Latitudes (SMALL) [*Gao et al.*, 2000], the Kakioka (KAK) magnetic observatory [*Tsunomura et al.*, 1994], and Ichon (ICH) branch of radio research laboratory [*Choi et al.*, 1997]. We use five station (CHD, ZYK, MGD, RIK, and EWA) data from CPMN and two station (BJI and THJ) data from SMALL. The magnetic shell parameter $L$ and geographic and corrected geomagnetic (CGM) coordinates of the ground stations are listed in Table 1. The $L$ and CGM values are calculated using the International Geomagnetic Reference Field converter at http://nssdc.gsfc.nasa.gov/space/cgm/cgm.html. The ground magnetometer data have a time resolution of 1 s, but we use 6-s averages from the original 1-s samples of the horizontal $H$ (northward) and $D$ (eastward) components.

## 3. Observations

A global image of the plasmasphere can be obtained by the Extreme Ultraviolet (EUV) instrument on the IMAGE satellite [e.g., *Goldstein et al.*, 2003]. Goldstein et al. showed that the $He^+$ edge, where the 30.4-nm $He^+$ emission sharply drops, coincides with a steep electron density gradient. That is, the $He^+$ edge corresponds to the plasmapause. Figure 1 shows the locations of the plasmapause (solid curve) determined using the method of *Goldstein et al.* [2003] from the IMAGE EUV data and ground stations (open circles) at 1519 UT on August 29, 2000. The solid circles outside the plasmapause at each local time indicate the locations where the plasma density reaches a value typical of the plasmatrough ($\sim$10 cm$^{-3}$) [*Denton et al.*, 2005]. We note that the plasma density in this study was obtained from a magnetospheric mass density model [*Denton et al.*, 2005], using the IMAGE satellite data, ground based data, and a model for the density variation along the field line. Comparing the $He^+$ edge and outer edge of the plasmapause, we can expect a sharp plasmapause in the postmidnight local time sector and a smoother gradient with plasma bulge in the duskside local time sector.

The equatorial mass density from Denton et al.'s model is plotted as a function of $L$ in Figure 2a. The curves with solid circles and open circles represent the equatorial mass density at 0100 MLT and 1900 MLT, respectively. As expected from Figure 1, steep and gradual plasmapause structures at 0100 MLT and 1900 MLT are confirmed. Using the dipole magnetic field, we calculated the local Alfvén velocity at the magnetic equator and plotted it in Figure 2b. There is an Alfvén barrier at $L = 3.8$ (2.9) at 0100 (1900) MLT. The barrier causes fast-mode waves to be trapped to establish a cavity-type mode in the plasmasphere [e.g., *Lee*, 1996]. Since the Alfvén barrier is associated with the plasmapause, the $He^+$ edge can be considered as a boundary where a fast-mode wave is trapped. Thus the plasmasphere on August 29, 2000 is strongly asymmetric with respect to longitude (i.e., much smaller in the duskside than in the postmidnight local time sector). Similar dawn-dusk asymmetric plasmasphere structure was reported during a geomagnetic storm [*Foster et al.*, 2002].

Figure 3a shows the $AL$ index during the interval from 1500 to 1600 UT on August 29, 2000. Since the 3-hour $Kp$ value corresponding to this time interval was 4+, the magnetosphere was not in a quiet condition. During this one-hour interval, $AL$ decreased to $\sim -440$ nT, except for the interval from 1523 to 1527 UT when it recovered to $\sim -70$ nT. The filtered (5-25 mHz) $H$-component magnetometer data from ICH ($L \sim 1.37$, local time (LT) $\sim$ UT+8.5 hours) and Pi2 power in the Pi2 frequency band (6.7-25 mHz) of the differenced ICH $H$ component are plotted in Figure 3b. There are four Pi2 power enhancements at ~1525, ~1534, ~1542, and ~1554 UT. We will focus on the first Pi2 event lasting three cycles from 1520 to 1530 UT because we have a model for the spatial structure of the plasmasphere at 1519 UT.

The unfiltered $H$ and $D$ components at mid and low latitude stations located at ~0.7-1.5 LT were plotted in Figure 4. There is sudden decrease in the $D$ component accompanied by the Pi2 event at ZYK and MGD. The negative $D$ perturbation would imply that the stations were located east of the center of the substorm current wedge [*Clauer and McPherron*, 1974]. The positive $H$ at MGD implies that the station was located west of the downward field-aligned current part of the wedge. Since the local time of MGD is nearly identical to that of ZYK, the negative $H$ perturbation at ZYK may be due to the westward electrojet current rather than the field-aligned current. There is no great negative $D$ perturbation at KAK, but the variations in the $H$ component are very similar to those at MGD.

In order to examine the Pi2 features more clearly along this latitude, the filtered (5-25 mHz) $H$ and $D$ components from the highlatitude (CHD), midlatitude (ZYK and MGD), and low-latitude (RIK and KAK) ground station data are plotted in Figure 5. Note the different vertical scale for the CHD $H$ component, which has the largest perturbation. As shown in Figure 1, CHD was located outside the plasmasphere and ZYK was close to the plasmapause. From the ground magnetic field data the spatial properties of the Pi2 pulsations can be investigated. First, the Pi2 pulsations in the $D$ component at all ground stations are nearly identical. That is, the Pi2 pulsations are not confined within the plasmasphere. Second, the Pi2 pulsations in both the $H$ and $D$ components at MGD, RIK, and KAK are nearly identical and show an out of phase signature. Third, the pulsations in the $D$ component are strongest at ZYK. This indicates that the field line of ZYK is close to the source of the Pi2 pulsation. Fourth, the $H$ component at ZYK is irregular and its amplitude is much smaller than that of the $D$ component. The amplitude of the perturbation in $H$ at CHD is much larger than that of the $D$ component at CHD (Note the different amplitude scale for the CHD $H$-component) and its waveform and period of the $H$ component slightly differ from those of the $D$ component. This indicates that the $H$ perturbation at CHD is not likely to be related to the Pi2 pulsations observed at the lower latitudes.

We now examine the longitudinal properties of the Pi2 pulsations at low latitudes. Figure 6 shows the filtered low-latitude ground station data. Well defined Pi2 pulsations were observed at THJ, BJI, ICH, and KAK with identical waveform and period. However, EWA, which was ∼5 hours away from midnight, did not detect the Pi2 pulsation. This implies that the Pi2 signal was localized to local times earlier than ∼0500 LT. This longitudinal localization is similar to that of a PBI-Pi2 that was observed without a corresponding substorm [*Kim et al.*, 2005]. The $H$ and $D$ components at THJ and BJI in the premidnight sector exhibit in-phase oscillations although the amplitude in $D$ is much smaller than that in $H$. However, the two components at KAK in the postmidnight sector oscillate out of phase. This longitudinal pattern of phase difference can be attributed to the location of Pi2 current system [*Lester et al.*, 1983] or can be expected in the cavity mode [*Allan et al.*, 1996]. We will discuss whether the Pi2 pulsations at low latitudes are generated by the plasmaspheric cavity mode resonance in next section.

If the longitudinal phase pattern is associated with the Pi2 current system, the polarization axis of the Pi2 pulsation at each station will be directed toward the center of the Pi2 current system. We use the autoregressive (AR) spectral analysis technique for the interval of the Pi2 pulsations to examine the polarization axis of the Pi2 pulsation. Detailed descriptions of this technique are given by *Takahashi et al.* [2002]. Figure 7 shows the AR spectral analysis of the KAK magnetic field data from 1523 to 1528 UT. The $H$ and $D$ components have a spectral enhancement at 11 mHz and the spectral power of $H$ is much larger than that of $D$. The polarization is 99%, the azimuth is 12°, corresponding to the northwest quadrant, and the ellipticity is close to zero, corresponding to linear polarization. The AR spectral analysis technique is applied to the mid and low-latitude ground data and the hodographs of the Pi2 pulsations at the ground stations are plotted in Figure 8. The hodographs show that the Pi2 pulsations are linearly polarized and that the major axes of the Pi2 pulsations are directed to a location near midnight, implying that the center of the Pi2 current system is between ICH and KAK. This polarization pattern is consistent with that predicted from the substorm current wedge mdodel [*Lester et al.*, 1983].

## 4. Discussion

### 4.1. Plasmaspheric Cavity Mode

The idea of the plasmaspheric cavity mode was proposed a long time ago by *Saito and Matsushita* [1968]. Supporting evidence for the plasmaspheric cavity mode model has been recently provided from ground-satellite observations in the inner magnetosphere. The evidence includes the radial variation of the amplitude and phase of the magnetic field [*Takahashi et al.*, 1992, 1995; *Han et al.*, 2004], the relationship between the electric and magnetic field [*Keiling et al.*, 2001; *Takahashi et al.*, 2001], the localization of compressional Pi2 signals [*Kim et al.*, 2001; *Takahashi et al.*, 2001], and multi-harmonic Pi2 oscillations in the plasmasphere [*Denton et al.*, 2002; *Takahashi et al.*, 2003].

A cavity mode can be established in the plasmasphere when there is a sharp inward density gradient at the plasmapause [e.g., *Allan et al.*, 1986; *Zhu and Kivelson*, 1989; *Lee*, 1996]. The frequency of the plasmaspheric cavity mode oscillation is determined by the size of the plasmasphere and the Alfvén speed. A simple formula for the frequency is

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

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 $\overline{V}_A$ is the effective Alfvén speed in the WKB solution [*Lee*, 1996]. This indicates that the fundamental frequency of the plasmaspheric cavity mode should be larger than the fundamental frequency of toroidal-mode standing Alfvén waves, which are called field line resonances (FLR), inside the plasmasphere.

For the fundamental frequency of the FLR we use a toroidal-mode equation [*Cummings et al.*, 1969] assuming dipole field geometry and the plasma mass density from *Denton et al.* [2005]. The radial profile of the calculated frequency for the fundamental FLR mode at the magnetic equator at 0100 MLT is plotted in Figure 9. The FLR profile shows that the observed Pi2 frequency is less than the fundamental FLR frequency inside the plasmasphere.

Recently *Fraser et al.* [2005] reported a heavy ion ($O^+$) torus near the plasmapause and showed that the FLR frequency discontinuity at the plasmapause is smoothed out. If we consider such a heavy ion effect near the plasmapause in our study, the fundamental FLR frequencies near the plasmapause will shift to lower frequencies. In some region inside the plasmapause, the fundamental FLR frequency will be lower than the observed Pi2 frequency. Such a region may be confined near the plasmapause because the heavy ion effect is not significant in the inner plasmasphere (see Figure 3 in *Fraser et al.* [2005]). Since the fundamental FLR frequency can be considered as a condition to determine cut-off boundaries of compressional waves [*Lee*, 1996], the plasmaspheric cavity mode could be established in such a limited space near the plasmapause. However, well-defined Pi2 oscillations were observed at low latitudes ($L < 2$). Therefore, we suggest that the plasmaspheric cavity mode is an unlikely source for the Pi2 pulsations at low latitudes described in this paper.

### 4.2. Mechanism for the Pi2 Pulsation

Let us next discuss other possible generation mechanisms for the Pi2 pulsation presented in our study. Because the amplitude of the Pi2 pulsation is strongly enhanced near the plasmapause, one could attribute the pulsation to an excitation of a surface wave at the plasmapause. We showed that the plasmasphere is strongly asymmetric along longitude. That is, the plasmapause is much closer at THJ (LT $\sim$ 22.3 hour) than at KAK (LT $\sim$ 0.8 hour). Then the expected frequency of the surface wave is higher in the premidnight local time sector than that in the postmidnight local time sector. However, the same frequency was observed at both stations, THJ and KAK, and the observed frequency was lower than the expected frequency of the surface wave on the plasmapause (24 mHz $\sim \sqrt{2}$ times the FLR frequency at 0100 MLT) [*Chen and Hasegawa*, 1974]. A statistical study of surface mode Pi2 pulsations at mid and low latitudes showed also that the frequency $\sim$11 mHz is lower than the statistical result at 0100 MLT at $Kp = 4$ [*Kosaka et al.*, 2002]. Thus, the surface wave model is not appropriate for our Pi2 event.

We showed that the orientation of the major axis of Pi2 polarization is directed toward the center of the current wedge, implying that the substorm current wedge model is a possible source for the Pi2 pulsations [*Lester et al.*, 1983]. However, our event occurred without a sudden decrease in $AL$, but with $AL$ slightly increased (see Figure 3). That is, a strong westward electrojet did not form at the auroral latitudes. This indicates that the event is not likely to be associated with the auroral current system generated during a substorm.

Recently, *Kepko et al.* [2001] suggested that periodic BBFs generate oscillating inertia currents in the near-Earth region of a strong dipole field where they decelerate and the currents are connected to the field-aligned currents. Field-aligned currents produce ground perturbations in the horizontal component at mid-latitude. The polarization pattern of the ground perturbations is nearly identical to that from *Lester et al.* [1983], which is driven by BBFs showing in Figure 8. Kepko et al. also suggested that BBF driven Pi2 pulsations can be excited during the absence of substorm. Thus, we suggest that our Pi2 event is driven by oscillating sources outside the plasmapause without any strong substorm signature.

We observed nearly identical oscillations in $D$ at mid latitudes (MGD, ZYK, and CHD, see Figure 5). The amplitude at ZYK was larger than that at CHD. This indicates that the field line connected to the source region (i.e., BBF braking point) is located between ZYK and CHD, but closer to ZYK. From the T96 magnetic field model [*Tsyganenko*, 1996], the CHD and ZYK field lines map to $X_{GSM} \sim -10.2\ R_E$ and $X_{GSM} \sim -4.2\ R_E$ in the plasma sheet, respectively. The braking point in our case is closer to Earth than geocentric distances of 10 to 15 Re in the plasma sheet suggested by *Shiokawa et al.* [1997]. The difference may be due to the disturbed geomagnetic condition, $Kp = 4+$. It should be mentioned why the waveform and period of the $H$ and $D$ components at CHD are slightly different, as shown in Figure 5. We suggest that the $H$ and $D$ perturbations at CHD are excited by a common source, but that their generation mechanism is different. The large amplitude of the $H$-component oscillation could be attributed to a field-line resonance or a transient Alfvénic perturbation excited by a series of compressional pulses associated with oscillatory earthward flows. As shown in Figure 9, the observed Pi2 frequency matches the FLR frequency at $L \sim 5.5$, roughly corresponding to the $L$ value at CHD. Note, however, that Denton et al.'s model did not include a density variation outside the plasmapasue and the CHD magnetic field line is mapped to greater $L$ value (∼10 $R_E$ from T96 model) than 5.5 because the magnetic field is stretched tailward in the nightside, so we need a study to examine the frequency of the high-latitude standing Alfvén wave in the nightside.

## 5. Conclusions

We have studied the Pi2 pulsations observed from high to low latitudes. The Pi2 pulsations exhibit a constant frequency over wide $L$ range, but localized to local time earlier than ∼0500 LT at low latitudes. This indicates that the source of our event is localized near midnight local time. Using a realistic magnetospheric mass density model, we examine whether our Pi2 pulsation can be explained by the plasmaspheric cavity mode. We find that the cavity-mode model is not appropriate for this Pi2 event. We suggest that the Pi2 pulsation in this study may be driven by external source such as oscillatory earthward flows.

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**Table 1.** List of Ground Stations

| | | Geographic | | Corrected Geomagnetic | |
|---|---|---|---|---|---|
| Station | $L$ | Latitude | Longitude | Latitude | Longitude |
| Chokurdakh (CHD) | 5.66 | 70.62° | 147.89° | 64.94° | 212.65° |
| Zyryanka (ZYK) | 4.03 | 65.75° | 150.78° | 59.88° | 217.25° |
| Magadan (MGD) | 2.91 | 59.97° | 150.86° | 53.76° | 219.20° |
| Rikubetsu (RIK) | 1.58 | 43.50° | 143.80° | 36.65° | 215.03° |
| Beijing (BJI) | 1.48 | 40.00° | 116.20° | 34.19° | 188.71° |
| Ichon (ICH) | 1.37 | 37.15° | 127.55° | 30.73° | 199.80° |
| Kakioka (KAK) | 1.33 | 36.13° | 140.11° | 29.15° | 211.63° |
| Ewa Beach (EWA) | 1.17 | 21.32° | 202.00° | 21.33° | 269.80° |
| Tonghai (THJ) | 1.11 | 24.00° | 102.70° | 17.23° | 174.55° |

**Figure 1.** The solid curve is the plasmapause location in SM (solar magnetic) coordinates at 1519 UT on August 29, 2000. The solid circles outside the plasmapause indicate at each local time indicate the locations where the plasma density reaches a typical value of the plasmatrough. The locations of ground stations at 1519 UT are plotted by the open circles.

**Figure 2.** (a) Equatorial mass density and (b) Equatorial Alfvén velocity. See text for the detail of the data analysis and model calculations.

**Figure 3.** (a) The auroral electrojet $AL$ index. (b) The filtered (5-25 mHz) $H$-component data and band-integrated Pi2 power at ICH.

**Figure 4.** $H$ and $D$ component magnetic field data at mid and low latitudes.

**Figure 5.** Filtered (5-25 mHz) $H$ and $D$ components from high latitude to low latitude. Note the different vertical scale for the CHD $H$ component.

**Figure 6.** Longitudinal properties of the Pi2 pulsations at low latitudes. The $H$ and $D$ components are filtered.

**Figure 7.** Autoregressive spectral analysis for the Pi2 interval at ICH. (a) Power spectra for the $H$ and $D$ components. (b) Polarization. (c) Azimuth of the major axis of polarization. The angle is measure from the positive $H$. The positive value indicates that the polarization axis lies in the northwest quadrant. (d) Ellipticity, defined positive for clockwise sense of rotation.

**Figure 8.** Magnetic field hodograms of the Pi2 pulsation observed at mid and low latitudes.

**Figure 9.** The solid curve is the fundamental toroidal mode frequency ($f_1$) and the horizontal solid line at 11 mHz indicates the observed Pi2 frequency.

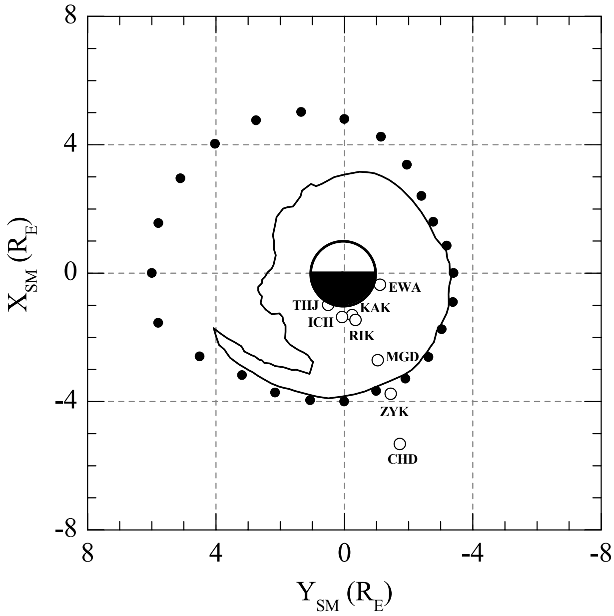



Figure 1

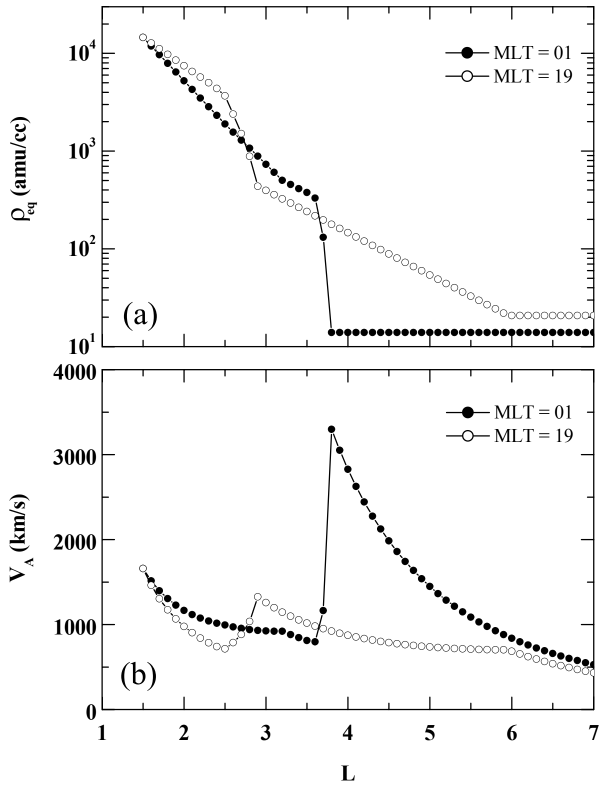



Figure 2

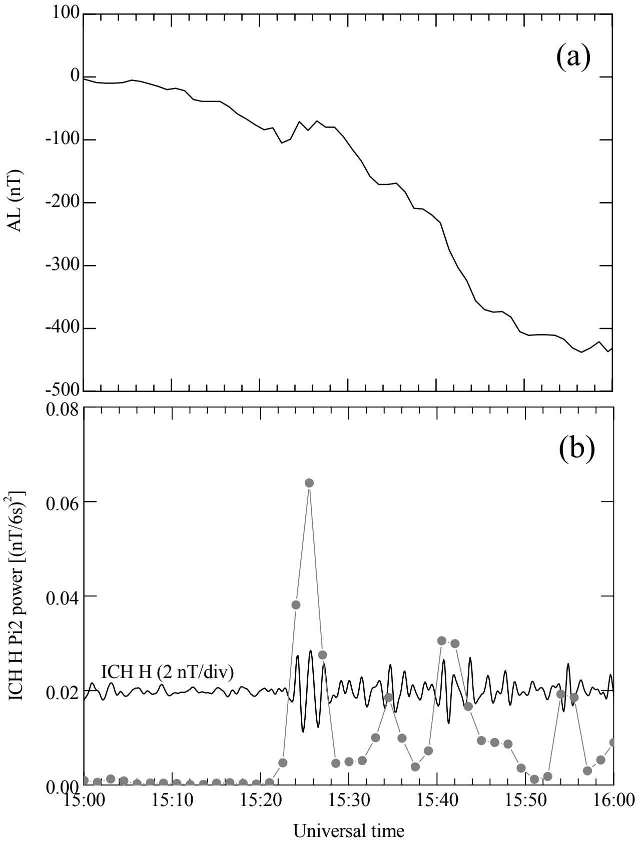

(a)
AL (nT)
100
0
-100
-200
-300
-400
-500
(b)
ICH H Pi2 power [(nT/6s)$^2$]
0.08
0.06
0.04
0.02
0.00
ICH H (2 nT/div)
15:00
15:10
15:20
15:30
15:40
15:50
16:00
Universal time

Figure 3

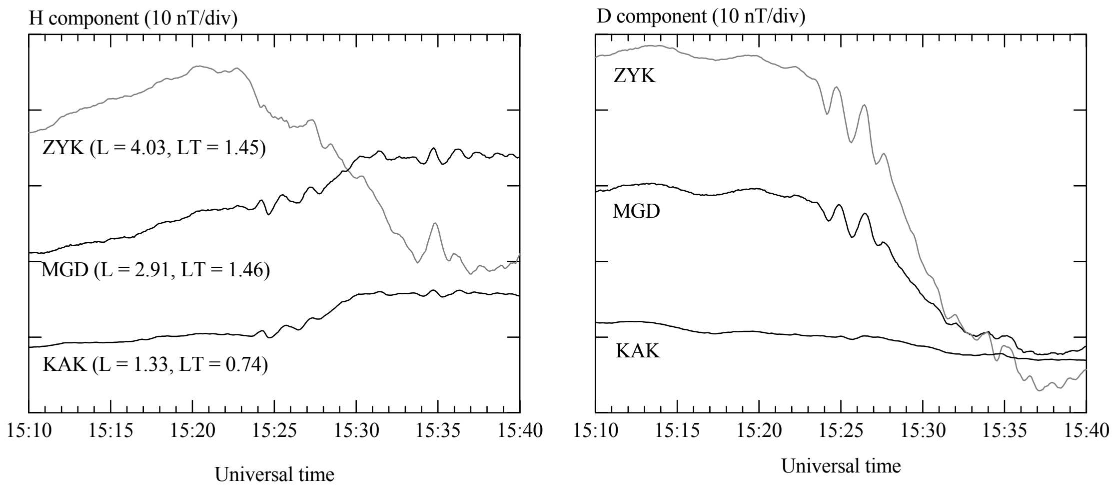
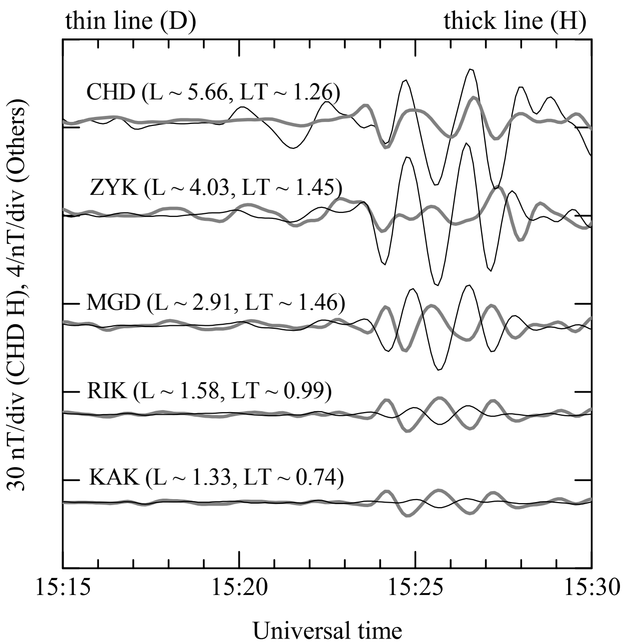
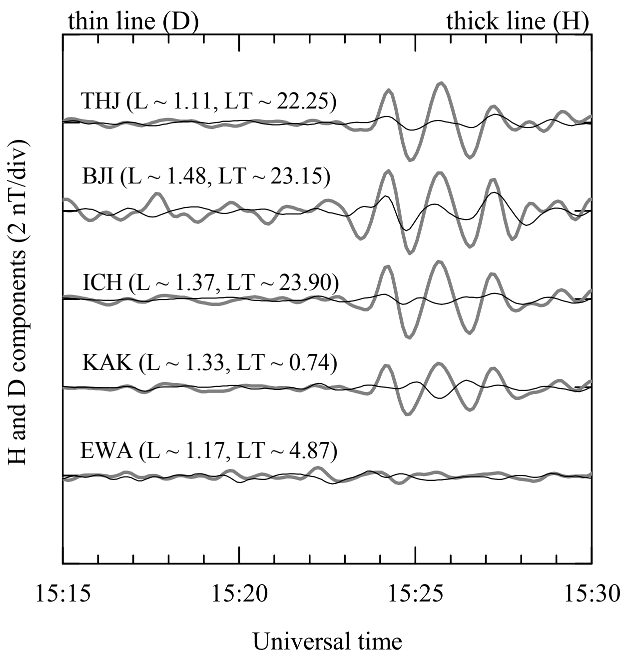

H component (10 nT/div)
ZYK (L = 4.03, LT = 1.45)
MGD (L = 2.91, LT = 1.46)
KAK (L = 1.33, LT = 0.74)
15:10
15:15
15:20
15:25
15:30
15:35
15:40
Universal time
D component (10 nT/div)
ZYK
MGD
KAK
15:10
15:15
15:20
15:25
15:30
15:35
15:40
Universal time

Figure 4



thin line (D)
thick line (H)
CHD (L ~ 5.66, LT ~ 1.26)
ZYK (L ~ 4.03, LT ~ 1.45)
MGD (L ~ 2.91, LT ~ 1.46)
RIK (L ~ 1.58, LT ~ 0.99)
KAK (L ~ 1.33, LT ~ 0.74)
30 nT/div (CHD H), 4/nT/div (Others)
15:15
15:20
15:25
15:30
Universal time


Figure 5



thin line (D)
thick line (H)
THJ (L ~ 1.11, LT ~ 22.25)
BJI (L ~ 1.48, LT ~ 23.15)
ICH (L ~ 1.37, LT ~ 23.90)
KAK (L ~ 1.33, LT ~ 0.74)
EWA (L ~ 1.17, LT ~ 4.87)
H and D components (2 nT/div)
15:15
15:20
15:25
15:30
Universal time


Figure 6

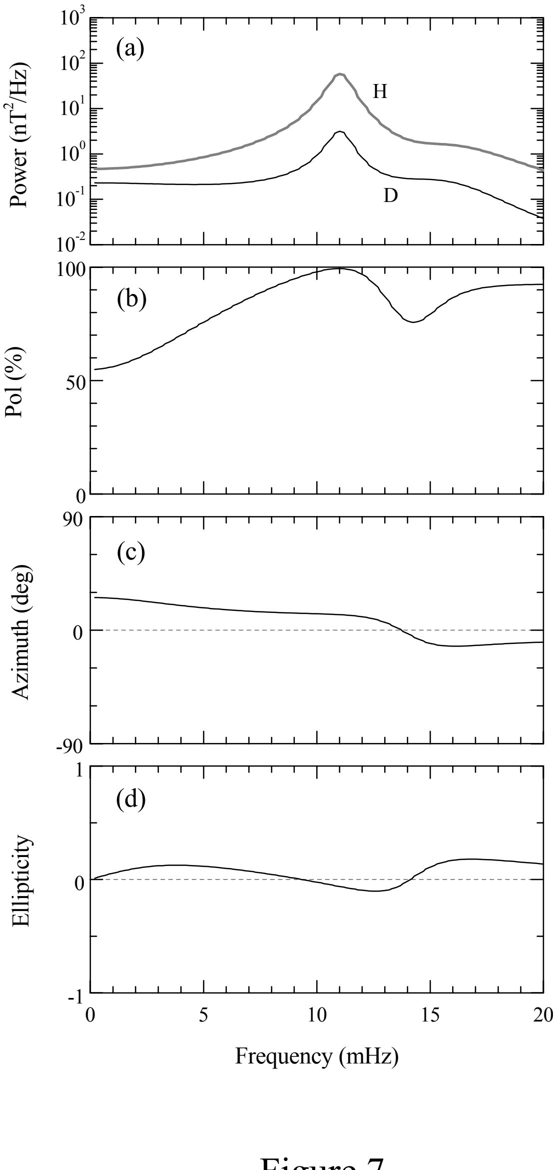

(a)
(b)
(c)
(d)
H
D
Power (nT²/Hz)
Pol (%)
Azimuth (deg)
Ellipticity
Frequency (mHz)
0
5
10
15
20
100
50
90
-90
1
-1

Figure 7

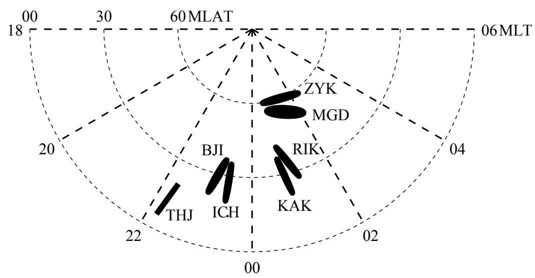
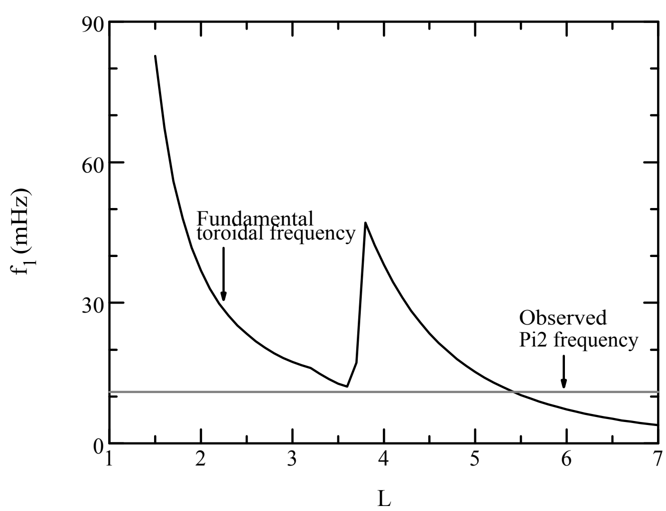



Figure 8



90
60
30
0
1
2
3
4
5
6
7
$f_1$ (mHz)
L
Fundamental
toroidal frequency
Observed
Pi2 frequency


Figure 9