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Pi2 pulsations in a small and strongly asymmetric plasmasphere

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[1] We study a Pi2 pulsation that occurred at ~1520 UT on 29 August 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, a global image of the plasmasphere was obtained from the IMAGE satellite, and the location of the plasmapause was clearly identified. The plasmasphere was small and strongly asymmetric in longitude. The plasmapause was located at $L \sim 2.4$, 3.8, and 3.3 near the duskside, midnight, and the dawnside, respectively. Using a magnetospheric mass density model constructed from the IMAGE satellite data and ground-based data, we examine whether the Pi2 pulsation observed inside the plasmasphere can be explained by a plasmaspheric cavity mode. We find that the frequency of 11 mHz is too low for a cavity mode in the plasmasphere. Thus the plasmaspheric cavity mode is not an appropriate model for our Pi2 event observed at midlatitudes and low latitudes. We discuss what determines its period and waveform inside such a small and asymmetric plasmasphere.

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1. Introduction

[2] 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.

[3] 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 midlatitude, diverted from the cross-tail current. Since the polarization pattern of Pi2 pulsations at midlatitude varies systematically relative to the center of the substorm current wedge (SCW) [*Lester et al.*, 1983], the SCW model is a favored generation mechanism of midlatitude 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 midlatitudes and low latitudes where the field lines are within the plasmapause.

[4] 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, 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*

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Table 1. List of Ground Stations

		Geographic		Corrected Geomagnetic	
Station	L	Latitude, deg	Longitude, deg	Latitude, deg	Longitude, deg
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

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.

[5] 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 are due to a quasiperiodic source external to the plasmasphere.

[6] In this paper we focus on a Pi2 pulsation that occurred at ~1520 UT on 29 August 2000. During the event the spatial structure of the plasmasphere was obtained by the IMAGE satellite and the plasmapause was well defined. Using multipoint ground-based data and a realistic magnetospheric mass density model (R. E. Denton et al., Realistic magnetospheric mass density model for 29 August 2000, submitted to *Journal of Atmospheric and Solar-Terrestrial Physics*, 2005, hereinafter referred to as Denton et al., submitted manuscript, 2005), we examine a generation mechanism of the Pi2 pulsation observed at low latitude.

[7] 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

[8] The data used in this study were acquired by ground-based magnetometers. The magnetometers belong to 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 data from five station (CHD, ZYK, MGD, RIK, and EWA) in CPMN and two station (BJI and THJ) in 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

[9] Global images 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) in L magnetic local time (MLT) plane at 1519 UT on 29 August 2000. We note that the CHD magnetic field line will be mapped to greater than ~5.7 because the high-latitude magnetic field lines are stretched tailward in the nightside. The solid circles outside the plasmapause at each local time indicate the locations where the plasma density reaches a value typical of the plasmatrough (~10 cm^{-3}) (Denton et al., submitted manuscript, 2005). We note that the plasma mass density in this study was obtained from a magnetospheric mass density model (Denton et al., submitted manuscript, 2005), derived

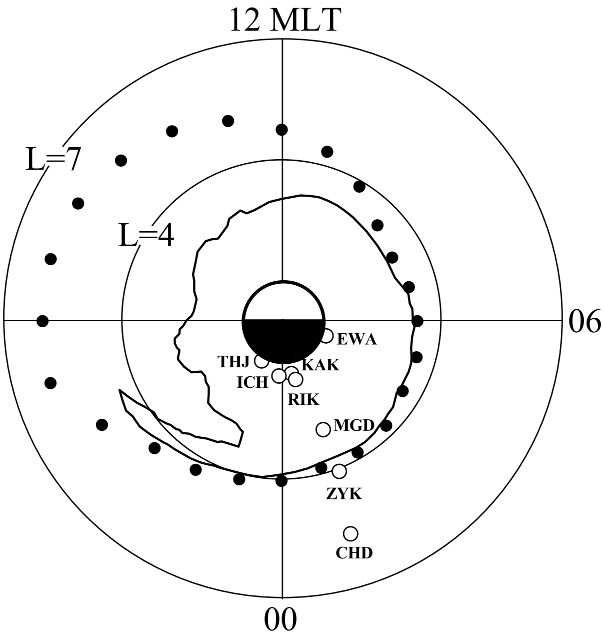

Figure 1. Plasmapause location in the L-MLT plane at 1519 UT on 29 August 2000 (solid curve). The solid circles outside the plasmapause at each local time indicate the locations where the plasma density reaches a typical value of the plasmatrough. The locations of ground stations at 1519 UT are plotted by the open circles.

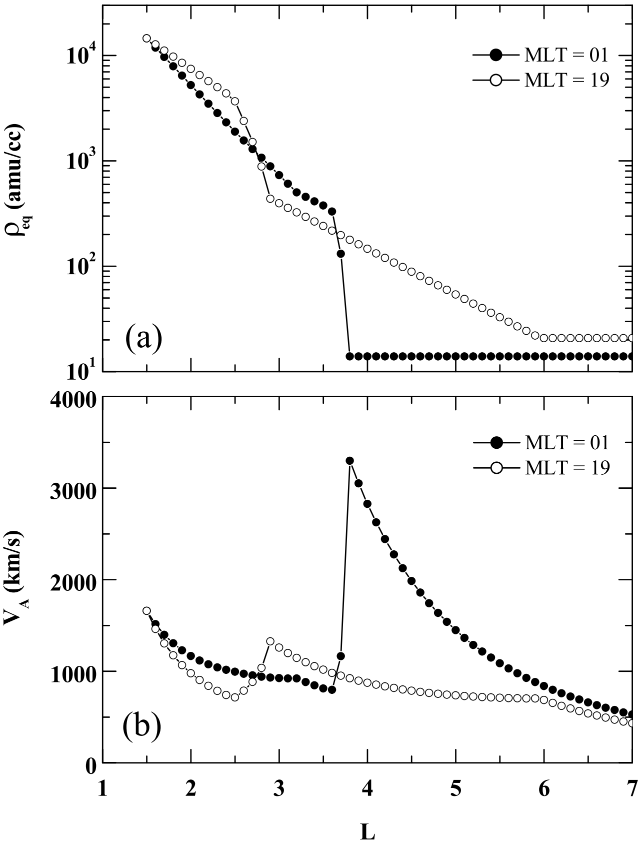

Figure 2. (a) Equatorial mass density and (b) equatorial Alfvén velocity. See text for details of the data analysis and model calculations.

from the IMAGE satellite data, field line resonance frequencies determined from ground magnetometer data, and a model for the density variation along the field line. In their model the effective ion mass in the plasmasphere was taken to be 1.4 amu, on the basis of a comparison of the mass density from field line resonance frequencies to local electron density. By comparing the He^+ edge and outer edge of the plasmapause, we find a sharp plasmapause in the postmidnight local time sector and a smoother gradient with plasma bulge in the duskside local time sector.

[10] The equatorial mass density from Denton et al.'s (submitted manuscript, 2005) 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. We can see steep and gradual plasmapause structures respectively at 0100 MLT and 1900 MLT. Using the dipole magnetic field, we calculated the local Alfvén velocity at the magnetic equator and plotted it in Figure 2b as a function of L for each local time. There is a sharp increase of the velocity 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 velocity 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 29 August 2000 is small in the duskside and 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].

[11] Figure 3a shows the *AL* index and CHD *H* during the interval from 1500 to 1600 UT on 29 August 2000. Since the 3-hour *Kp* value corresponding to this time interval was 4+, the magnetosphere was not in a quiet condition. The plasmapause, according to the empirical relationship between the *Kp* index and the plasmapause distance [*Chappell et al.*, 1970], is located somewhere between L = 3 and L = 4. This estimated location is consistent with the location of the near-midnight plasmapause shown in Figure 2a. During this 1-hour interval, *AL* decreased to ∼−440 nT, except for the interval from 1522 to 1527 UT when it recovered to ∼−70 nT. There was sudden decrease in the *H* component at CHD (local time (LT) ∼ UT + 9.9 hours) at 1522 UT, indicating a local enhancement of westward electrojet current. The current wedge formation may be localized in the CHD local time and may not appear in the *AL* index, which is a longitudinal average of *H* component variations.

[12] The filtered (6–25 mHz) *H* component magnetometer data from ICH (L ∼ 1.37, LT ∼ UT + 8.5 hours) and Pi2 power in the Pi2 frequency band (6–25 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. This event occurred when the CHD *H* component

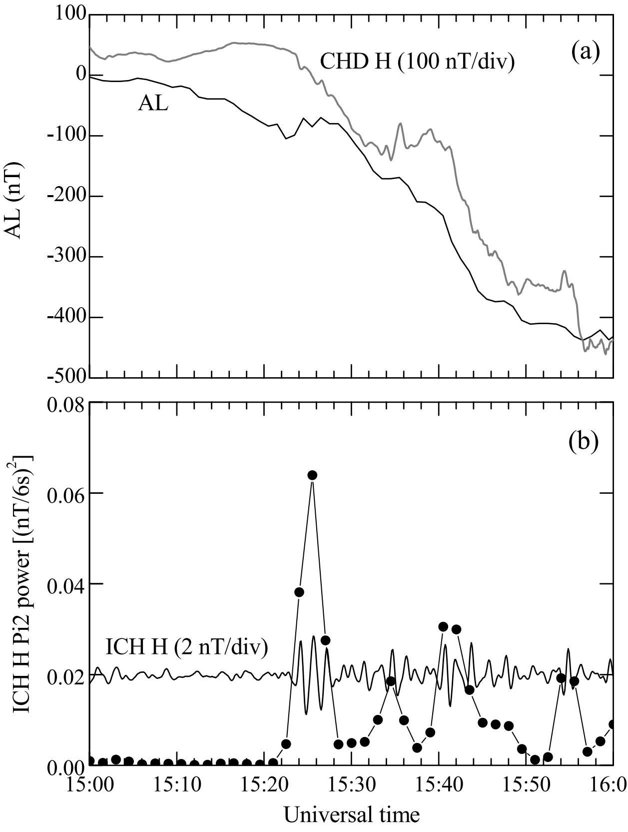

Figure 3. (a) Auroral electrojet *AL* index and CHD *H* component. (b) Filtered (6–25 mHz) *H* component data and band-integrated Pi2 power at ICH.

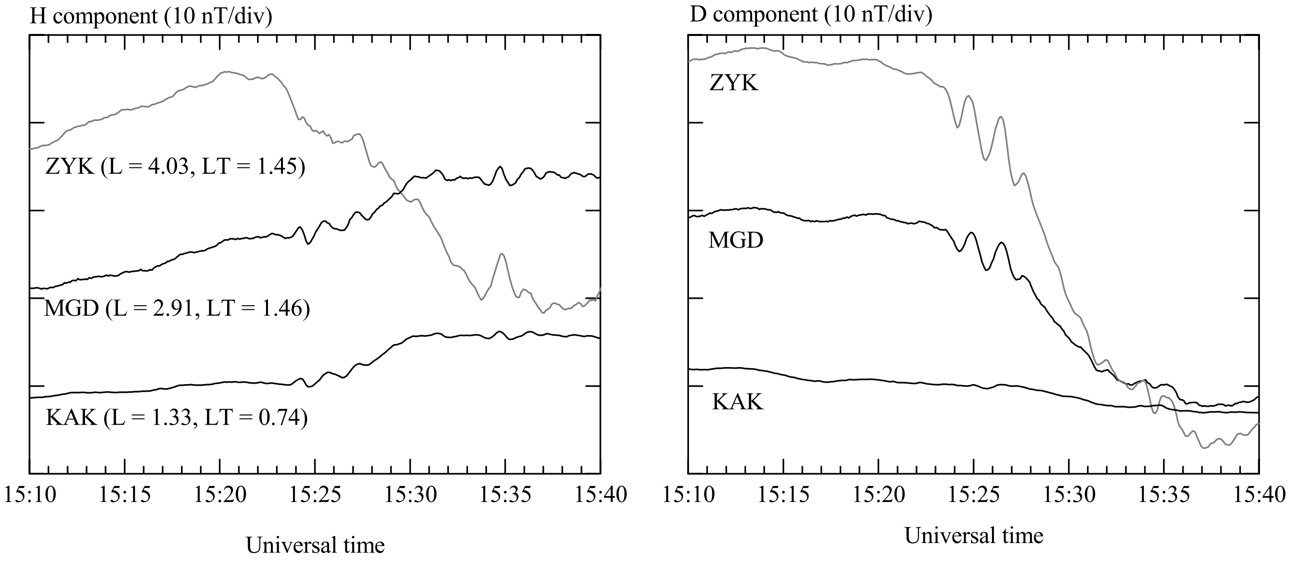

Figure 4. *H* and *D* component magnetic field data at midlatitudes and low latitudes.

started to decrease. Thus the Pi2 pulsation is a substorm-associated event.

[13] The unfiltered *H* and *D* components at midlatitude and low-latitude stations located at ~0.7–1.5 LT were plotted in Figure 4. There is a sudden decrease in the *D* component accompanied by the Pi2 event at ZYK and MGD. The negative *D* perturbation implies 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.

[14] In order to examine the Pi2 features more clearly along latitude, the filtered (5–25 mHz) *H* and *D* components from the high-latitude (CHD), midlatitude (ZYK and MGD), and low-latitude (RIK and KAK) ground stations 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.

[15] 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. At EWA, which was ~5 hours away from midnight, similar waveform in *H* was detected, but its amplitude is much smaller (by a factor of ~4) than that at other low-latitude stations. This implies that the power of the Pi2 signal was localized to local times

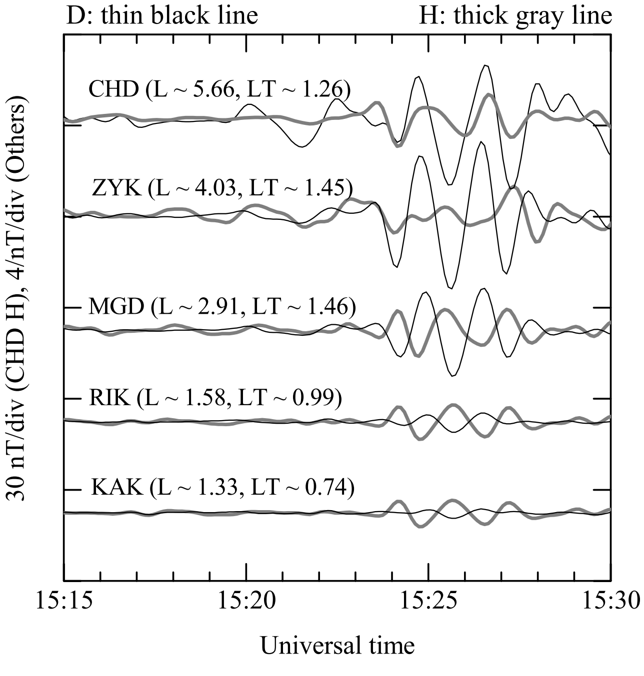

Figure 5. Filtered (5–25 mHz) *H* and *D* components from high latitude to low latitude. Note the different vertical scale for the CHD *H* component.

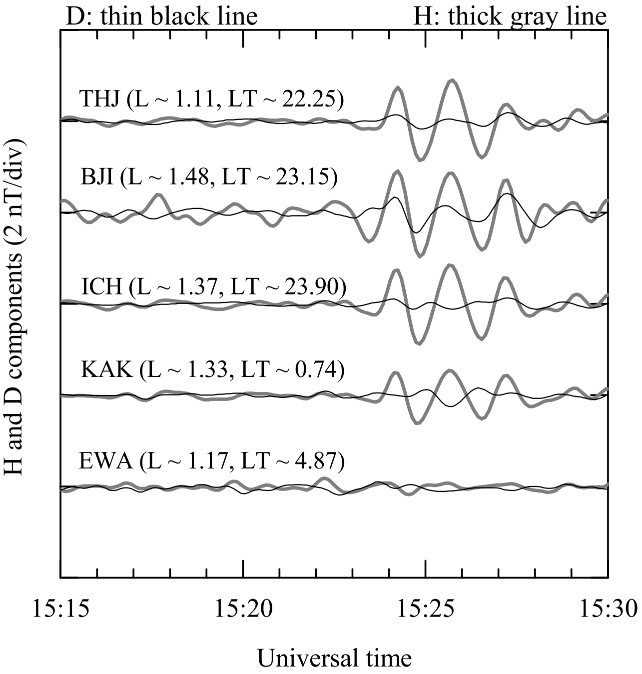

Figure 6. Longitudinal properties of the Pi2 pulsations at low latitudes. The *H* and *D* components are filtered.

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.

[16] 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*. At this frequency 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 was applied to the data from stations shown in Figures 5 and 6, and the hodographs that incorporate the azimuth and ellipticity at 11 mHz 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 model [*Lester et al.*, 1983].

4. Discussion

4.1. Plasmaspheric Cavity Mode

[17] 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

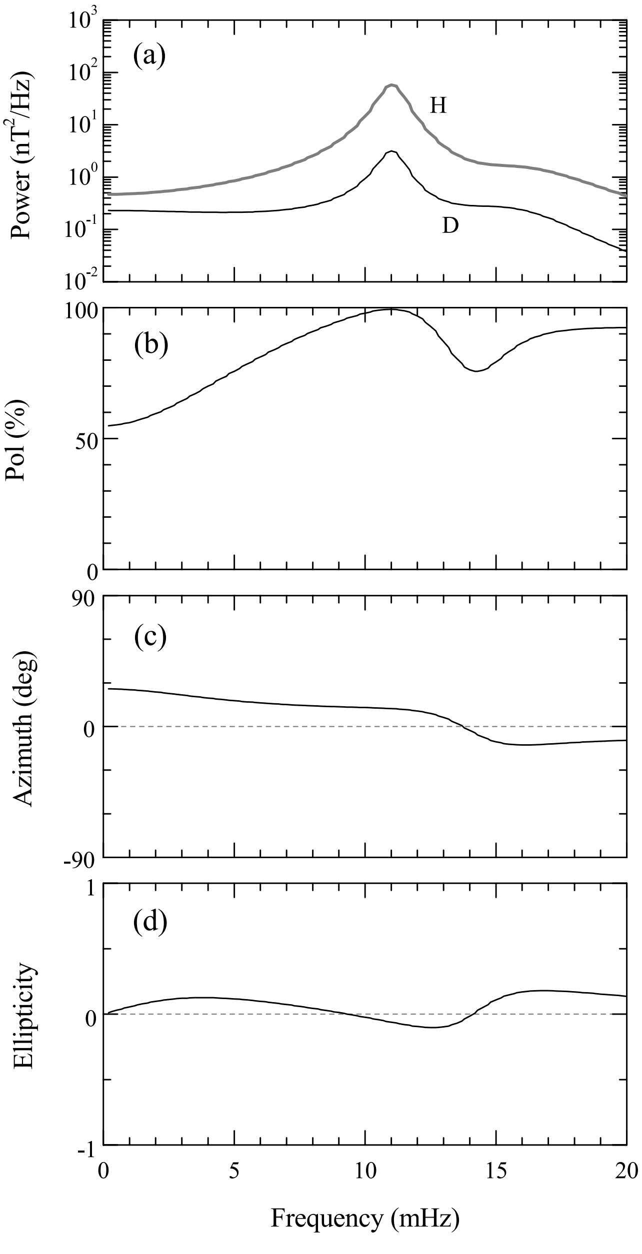

Figure 7. Autoregressive spectral analysis for the Pi2 interval at ICH. (a) Power spectra for the *H* and *D* components. (b) Polarization. (c) Azimuth of the major axis of polarization. The angle is measure from the positive *H*. The positive value indicates that the polarization axis lies in the northwest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

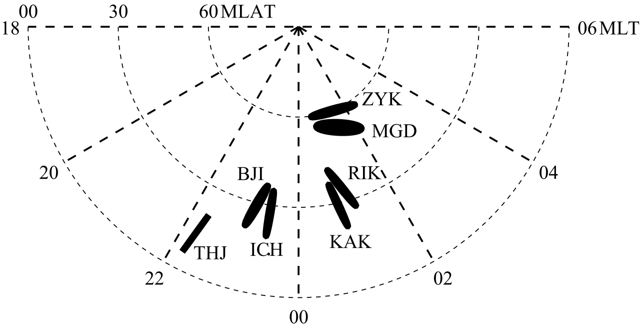

Figure 8. Magnetic field hodograms of the Pi2 pulsation observed at midlatitudes and low latitudes.

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, 2003], the localization of compressional Pi2 signals [*Kim et al.*, 2001; *Takahashi et al.*, 2001], and multiharmonic Pi2 oscillations in the plasmasphere [*Denton et al.*, 2002; *Takahashi et al.*, 2003].

[18] 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 can be approximated by

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

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 $\overline{V}_A$ is the effective Alfvén speed in the WKB solution [*Lee*, 1996]. Equation (1) 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),

$$\omega_{FLR} = \pi V_A/L_{\|} \qquad (2)$$

inside the plasmasphere, where V_A is the local Alfveén speed and $L_{\|}$ is the field line length. Note that $L_{\|}$ is much larger than L_z in a dipole geometry [*Lee*, 1996].

[19] 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. (submitted manuscript, 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.

[20] 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 a lower value. 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 O^+ is not significant in the inner plasmasphere [see *Fraser et al.*, 2005, Figure 3]. Since the fundamental FLR frequency can be considered as a condition to determine cutoff 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 very low latitudes ($L <$ 1.3). This indicates that the azimuthal wave number m should be small [*Lee*, 1996]. Typical azimuthal wave numbers of the low-latitude Pi2 pulsations associated with plasmaspheric cavity mode are less than 3 [*Li et al.*, 1998]. If the Pi2 pulsations in our study are due to fast mode resonance in the plasmasphere, they may be observed globally on the nightside. However, our event was localized near midnight local time (see Figure 6), indicating that the source of the Pi2 pulsations may not be the plasmasphere itself.

[21] We can make a rough estimate of the time-of-flight cavity mode frequency using the plasmapause (located at L = 3.8) and averaged Alfveén speed (V_A = 1000 km/s) at 0100 MLT (see Figures 1 and 2). The estimated fundamental cavity mode frequency is ∼28 mHz. This frequency is much higher than the observed Pi2 frequency, ∼11 mHz. Recently, *Lee and Kim* [1999] suggested that Pi2 pulsations are strongly associated with plasmasphere virtual resonance (PVR) and that the PVR mode extends beyond the plasmapause. Thus Pi2 pulsations are not necessarily localized and confined within the plasmasphere. This indicates that the PVR mode frequency is lower than the plasmaspheric cavity mode frequency. The maximum wavelength of the PVR can also be limited by the radial distance from ground to the plasmapause since the antinodal point should remain inside the plasmasphere. Then, the lowest frequency possible in this case would be almost half cavity mode frequency ∼14 mHz. The estimated frequency is calculated for the one-dimensional mode. If the PVR mode is calculated for the three-dimensional mode because it is also determined by

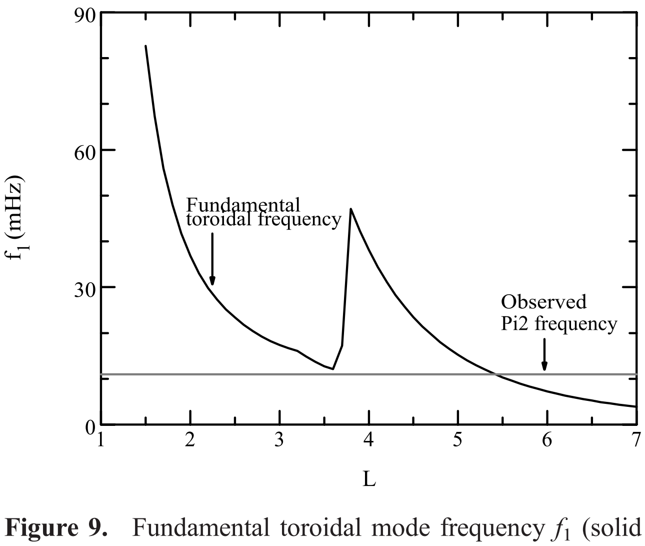

Figure 9. Fundamental toroidal mode frequency f_1 (solid curve); the horizontal solid line at 11 mHz indicates the observed Pi2 frequency.

the size of the plasmasphere and the Alfvén speed, the estimated frequency is higher than the ~14 mHz.

4.2. Mechanism for the Pi2 Pulsation

[22] 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 ~22.3 hour) than at KAK (LT ~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 ~ $\sqrt{2}$ times the FLR frequency at 0100 MLT) [*Chen and Hasegawa*, 1974]. A statistical study of surface mode Pi2 pulsations at midlatitudes and low latitudes showed also that the frequency ~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.

[23] At the time of the Pi2 pulsations, there was a sudden decrease in the CHD H, indicating a local enhancement of westward electrojet current. Thus our event is associated with the auroral current system generated during a substorm. We showed that the orientation of the major axis of Pi2 polarization is directed toward the center of the current wedge. Thus we suggest that the field-aligned current oscillation model is a possible source for the Pi2 pulsations [*Lester et al.*, 1983].

[24] Recently, the driven Pi2 mechanism was proposed by *Kepko and Kivelson* [1999] and *Kepko et al.* [2001]. The authors showed several examples of Pi2 waves and BBF oscillations that have nearly identical waveforms and suggested that low-latitude Pi2 pulsations can be directly driven by BBFs. *Shiokawa et al.* [1998] reported that Pi2 pulsations in the plasmasphere can be generated by compressional pulses produced by BBFs and suggested that BBF is a possible impulsive source. Thus BBFs can provide combined sources: monochromatic (directly driven oscillation) source and impulsive (cavity resonance) source. If the plasmasphere is too small and asymmetric to excite cavity mode or PVR mode in the Pi2 frequency band, we can expect BBF-driven Pi2 pulsations in such a small and asymmetric plasmasphere because the period and waveform of Pi2 pulsations are determined at the source outside the plasmasphere and the plasmasphere is merely a passive medium into which the pulsations propagate.

[25] Although we favor directly driven oscillation source rather than cavity resonance source for our Pi2 pulsations, we exclude that the Pi2 pulsations directly propagate from the source region to low latitude because the Pi2 amplitude in the D component at ZYK is larger than that at CHD. *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 midlatitude. The polarization pattern of the ground perturbations driven by BBFs is nearly identical to that from *Lester et al.* [1983]. Thus we suggest that the source of our events is the field-aligned current oscillation associated with BBFs.

[26] We observed nearly identical oscillations in D at high latitudes and midlatitudes (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 and Stern*, 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 (~5.7) at CHD. Note, however, that Denton et al.'s (submitted manuscript, 2005) model did not include a density variation outside the plasmapause and the CHD magnetic field line is mapped to greater L value (~10 R_E from T96 model) than ~5.7 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

[27] We have studied the Pi2 pulsations observed from high to low latitudes. The Pi2 pulsations exhibit a constant frequency over wide L range. 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 existing cavity mode model does not explain some key features of our Pi2 event. To improve our understanding of Pi2 pulsations in such a small and asymmetric plasmasphere, we need a numerical simulation based on the real distribution of plasma in and around the plasmapause. We have discussed a possible model for our Pi2 event and suggest that the source of the Pi2 pulsation in this study is the field-aligned current oscillation associated with BBFs. Unfortunately, we do not have magnetotail observations to confirm that BBFs directly drive the Pi2 pulsations in the small and asymmetric plasmasphere. Therefore our present data do not give direct evidence that the Pi2 pulsations in this study are driven by an external source such as BBFs. A comprehensive statistical analysis of the relationship between BBFs and Pi2 pulsations is necessary to determine the Pi2 source mechanism.

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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.

Allan, W., F. W. Menk, B. J. Fraser, Y. Li, and S. P. White (1996), Are low-latitude Pi2 pulsations cavity/waveguide modes?, *Geophys. Res. Lett.*, *23*, 765.

Bauer, T. M., W. Baumjohann, and R. A. Treumann (1995), Neutral sheet oscillations at substorm onset, *J. Geophys. Res.*, *100*, 23,737.

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.

Chappell, C. R., K. K. Harris, and G. W. Sharp (1970), A study of the influence of magnetic activity on the location of the plasmapause as measured by OGO 5, *J. Geophys. Res.*, *75*, 50.

Chen, L., and A. Hasegawa (1974), A theory of long-period magnetic pulsations: 2. Impulse excitation of surface eigenmode, *J. Geophys. Res.*, *79*, 1033.

Choi, C. R., K. S. Cho, J. K. Park, G. H. Lee, S. H. Lee, S. K. Sung, and D. H. Lee (1997), Installation of the geomagnetic field measurement network and initial measurement result (in Korean), *J. Astron. Space Sci.*, *14*, 126.

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.

Cummings, W. D., R. J. O'Sullivan, and P. J. Coleman Jr. (1969), Standing Alfvén waves in the magnetosphere, *J. Geophys. Res.*, *74*, 778.

Denton, R. E., D. H. Lee, K. Takahashi, J. Goldstein, and R. Anderson (2002), Quantitative test of the cavity resonance explanation of plasmaspheric Pi2 frequencies, *J. Geophys. Res.*, *107*(A7), 1093, doi:10.1029/2001JA000272.

Foster, J. C., P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich (2002), Ionospheric signatures of plasmaspheric tails, *Geophys. Res. Lett.*, *29*(13), 1623, doi:10.1029/2002GL015067.

Fraser, B. J., J. L. Horwitz, J. A. Slavin, Z. C. Dent, and I. R. Mann (2005), Heavy ion mass loading of the geomagnetic field near the plasmapause and ULF wave implications, *Geophys. Res. Lett.*, *32*, L04102, doi:10.1029/2004GL021315.

Fukunishi, H. (1975), Polarization changes of geomagnetic Pi2 pulsations associated with the plasmapause, *J. Geophys. Res.*, *80*, 98.

Fujita, S., and K.-H. Glassmeier (1995), Magnetospheric cavity resonance oscillations with energy flow across the magnetopause, *J. Geomagn. Geoelectr.*, *47*, 1277.

Fujita, S., H. Nakata, M. Itonaga, A. Yoshikawa, and T. Mizuta (2002), A numerical simulation of the Pi2 pulsations associated with the substorm current wedge, *J. Geophys. Res.*, *107*(A3), 1034, doi:10.1029/2001JA900137.

Gao, Y. F., P. J. Chi, G. Le, C. T. Russell, D. M. Yang, X. Zhou, S. F. Yang, V. Angelopoulos, and F. K. Chun (2000), Sino-magnetic array at low latitudes (SMALL) including initial results from the sister sites in the United States, *J. Geomagn. Geoelectr.*, *44*, 253.

Goldstein, J., M. Spasojević, P. H. Reiff, B. R. Sandel, W. T. Forrester, D. L. Gallagher, and B. W. Reinisch (2003), Identifying the plasmapause in IMAGE EUV data using IMAGE RPI in situ steep density gradients, *J. Geophys. Res.*, *108*(A4), 1147, doi:10.1029/2002JA009475.

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*, A10209, doi:10.1029/2004JA010576.

Keiling, A., J. R. Wygant, C. Cattell, K.-H. Kim, C. T. Russell, D. K. Milling, M. Temerin, F. S. Mozer, and C. A. Kletzing (2001), Pi2 pulsations observed with the Polar satellite and ground stations: Coupling of trapped and propagating fast mode waves to a midlatitude field line resonance, *J. Geophys. Res.*, *106*, 25,891.

Kepko, L., and M. Kivelson (1999), Generation of Pi2 pulsations and bursty bulk flows, *J. Geophys. Res.*, *104*, 25,021.

Kepko, L., M. Kivelson, and K. Yumoto (2001), Flow bursts, braking, and Pi2 pulsations, *J. Geophys. Res.*, *106*, 1903.

Kim, K.-H., K. Takahashi, D.-H. Lee, N. Lin, and C. A. Cattell (2001), A comparison of Pi2 pulsations in the inner magnetosphere and magnetic pulsations at geosynchronous orbit, *J. Geophys. Res.*, *106*, 18,865.

Kim, K.-H., K. Takahashi, D.-H. Lee, P. R. Sutcliffe, and K. Yumoto (2005), Pi2 pulsations associated with poleward boundary intensifications during the absence of substorms, *J. Geophys. Res.*, *110*, A01217, doi:10.1029/2004JA010780.

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-latitude, *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.

Lee, D.-H. (1998), On the generation mechanism of Pi2 pulsations in the magnetosphere, *Geophys. Res. Lett.*, *25*, 583.

Lee, D.-H., and K. Kim (1999), Compressional MHD waves in the magnetosphere: A new approach, *J. Geophys. Res.*, *104*, 12,379.

Lee, D.-H., and R. L. Lysak (1999), MHD waves in a three-dimensional dipolar magnetic field: A search for Pi2 pulsations, *J. Geophys. Res.*, *104*, 28,691.

Lester, M., W. J. Hughes, and H. J. Singer (1983), Polarization patterns of Pi2 magnetic pulsations and the substorm current wedge, *J. Geophys. Res.*, *88*, 7958.

Li, Y., B. J. Fraser, F. W. Menk, D. J. Webster, and K. Yumoto (1998), Properties and sources of low and very low latitude Pi2 pulsations, *J. Geophys. Res.*, *103*, 2343.

Lin, C. A., L. C. Lee, and Y. J. Sun (1991), Observations of Pi2 pulsations at a very low latitude (L = 1.06) station and magnetospheric cavity resonances, *J. Geophys. Res.*, *96*, 21,105.

Olson, J. V. (1999), Pi2 pulsations and substorm onsets: A review, *J. Geophys. Res.*, *104*, 17,499.

Osaki, H., K. Takahashi, H. Fukunishi, T. Nagatsuma, H. Oya, A. Matsuoka, and D. K. Milling (1998), Pi2 pulsations observed from the Akebono satellite in the plasmasphere, *J. Geophys. Res.*, *103*, 17,605.

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

Saito, T., and S. Matsushita (1968), Solar cycle effects on geomagnetic Pi2 pulsations, *J. Geophys. Res.*, *73*, 267.

Shiokawa, K., W. Baumjohann, and G. Haerendel (1997), Braking of high-speed flows in the near-Earth tail, *Geophys. Res. Lett.*, *24*, 1179.

Shiokawa, K., et al. (1998), High-speed ion flow, substorm current wedge, and multiple Pi2 pulsations, *J. Geophys. Res.*, *103*, 4491.

Stuart, W. F. (1974), A mechanism of selective enhancement of Pi2's by the plasmasphere, *J. Atmos. Terr. Phys.*, *36*, 851.

Sutcliffe, P. R. (1975), The association of harmonics in Pi2 power spectra with the plasmapause, *Planet. Space Sci.*, *23*, 1581.

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 K. Yumoto (1992), AMPTE CCE observations of Pi2 pulsations in the inner magnetosphere, *Geophys. Res. Lett.*, *19*, 1447.

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., 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., K. Liou, and K. Yumoto (2002), Correlative study of ultraviolet aurora and low-latitude Pi2 pulsations, *J. Geophys. Res.*, *107*(A12), 1417, doi:10.1029/2002JA009455.

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.*, *100*(A5), 1210, doi:10.1029/2002JA009761.

Tsunomura, S., A. Yamazaki, T. Tokumoto, and Y. Yamada (1994), The new system of Kakioka automatic standard magnetometer, *Mem. Kakioka Magn. Obs.*, *25*, 3.

Tsyganenko, N. A., and D. P. Stern (1996), Modeling the global magnetic field of the large-scale Birkeland current systems, *J. Geophys. Res.*, *101*, 27,187.

Yeoman, T. K., and D. Orr (1989), Phase and spectral power of mid-latitude Pi2 pulsations: Evidence for a plasmaspheric cavity resonance, *Planet. Space Sci.*, *37*, 1367.

Yumoto, K., et al. (1996), The STEP 210° magnetic meridian network project, *J. Geomagn. Geoelectr.*, *48*, 1297.

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.

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