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Local time dependence of the dominant frequency of Pi2 pulsations at mid- and low-latitudes

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We carried out a statistical analysis of Pi2 pulsations using the geomagnetic field data obtained at three ground stations. A local time dependence of the dominant frequency of Pi2 was found on the nightside. The frequency of mid-latitude Pi2 pulsations is lower on the dusk side than that on the dawn side. This tendency is attributed to the shape of the plasmasphere which bulges out to the dusk side. It was confirmed that the Pi2 frequency depends also on the geomagnetic activity measured with Kp index. During the disturbed periods, Pi2 pulsations have higher frequency than that in the quiet periods. This dependence is interpreted to be caused by the size of the plasmapause which is smaller under the disturbed conditions than that under the quiet conditions. The dominant frequency of Pi2 pulsations at lower latitudes has a peak in post-midnight, and a Kp dependence similar to that at mid-latitudes is also observed. However, the result for low-latitude Pi2's is different from that for mid-latitude Pi2. We consider that the dominant mechanism of mid-latitude Pi2 is the plasmaspheric surface wave. In order to examine the idea that the surface wave on the plasmapause is the dominant mechanism of Pi2 pulsations at mid-latitudes, we estimated the resonance frequency of the surface wave on the plasmapause using a plasmaspheric model which includes the effect of the plasmaspheric bulge. The estimated frequency of the surface wave is higher on the dawn side than that on the dusk side, which is essentially consistent with the observational results. The predicted frequency under quiet conditions (Kp $\leq$ 3) is nearly equal to the observed Pi2 frequency at mid-latitudes. These results suggest that the dominant frequency of Pi2 pulsations at mid-latitudes depends on the structure of the plasmapause.

1. Introduction

A Pi2 pulsation is defined as an oscillation of geomagnetic field in the period range from 40 to 150 seconds for dominant frequency having irregular components. It usually occurs at substorm onset and is regarded as a good indicator of a substorm onset (e.g., Saito *et al.*, 1976). Pi2 pulsations are considered to be the magnetohydrodynamic (MHD) waves released when the near-Earth magnetotail has a rapid configurational change at a substorm onset (e.g., Osaki *et al.*, 1998; Kepko *et al.*, 2001).

There have been many researches on the generation mechanism of Pi2 pulsations. The amplitude of Pi2 pulsations has the primary maximum around the auroral electrojet latitudes and the secondary maximum near the foot point of the plasmapause (e.g., Kuwashima and Saito, 1981). This secondary maximum is not always observed since it is weak and narrow in latitude. The phase in the H component is reversed across the plasmapause while that in the D component remains constant (e.g., Fukunishi, 1975; Lester and Orr, 1983; Yeoman and Orr, 1989). From these results, it is considered that the plasmasphere plays an important role for mid- and low-latitude Pi2 pulsations.

Two fundamentally different models have been proposed for mid- and low-latitude Pi2 pulsations (e.g., Olson, 1999; Yumoto *et al.*, 2001). One is a surface wave on the plasmapause (e.g., Sutcliffe, 1975; Lester and Orr, 1983), and the other is a cavity resonance in the plasmasphere (e.g., Yeoman and Orr, 1989; Cheng *et al.*, 2000).

Sutcliffe (1975) first suggested that the amplitude maximum and harmonic structure seen near the expected plasmapause position indicate that a surface wave on the plasmapause was the most credible mechanism. Lester and Orr (1983) argued that the surface wave on the plasmapause can explain these characteristics of Pi2 pulsations at mid-latitudes from the analysis of the geomagnetic data observed at ground stations.

On the other hand, Yeoman and Orr (1989) compared the ground station data with the estimation of the Pi2 frequency from a 2-D plasmaspheric model. They concluded that the most likely mechanism for the secondary amplitude maximum of Pi2 pulsations at mid-latitudes is not the surface wave but the plasmaspheric cavity resonance. Takahashi *et al.* (1999) reported that an oscillation with finite compressional magnetic component is observed by CRRES in a dense plasma, and the waveform matched that of the ground Pi2 pulsation. They suggested that mid- and low-latitude Pi2 pulsations are related to the fast mode oscillation in the plasmasphere. Cheng *et al.* (2000) reported that the ratio of the first four harmonic frequencies of Pi2 pulsations at low-

Table 1. The coordinates of geomagnetic stations in this study.

	Geographic		Geomagnetic		
Station Name	Latitude [deg.]	Longitude [deg.]	Latitude [deg.]	Longitude [deg.]	L value
Kakioka	36.2	140.2	26.9	−151.7	1.3
Crozet	−46.4	51.9	−51.5	112.4	2.6
Port Aux Français	−49.4	70.3	−57.2	131.8	3.4

latitudes is consistent with that of the plasmaspheric cavity mode resonance simulated in the box model of the magnetosphere.

These theories are mainly based on the examinations of latitudinal dependences of Pi2 pulsations. However, there are few researches which treat a longitudinal or local time dependence of Pi2 frequency at mid- and low-latitudes. In this paper, we analyzed Pi2 pulsations at mid- and low-latitude stations, and found a local time and a geomagnetic activity dependences of the Pi2 dominant frequency. These results are compared with the theoretical estimation of the frequency of the plasmapause surface wave by using a plasmaspheric model.

2. Data Set

The geomagnetic field data we use in this paper were obtained with the fluxgate magnetometers at three ground stations in low- or mid-latitudes; Kakioka (KAK; L = 1.3), Crozet (CZT; L = 2.6), and Port Aux Français (PAF; L = 3.4). The data period analyzed in this paper is from January 1984 to December 1985. The coordinates of the stations are listed in Table 1. The data from KAK have one second resolution. The sampling interval of the original data from CZT and PAF is two seconds and we converted them to apparent one second resolution data by duplicating the same value to the next second for each data point.

The Pi2 pulsations examined in this paper were automatically detected by a wavelet analysis. The method is developed by Nosé *et al.* (1998), which is suitable for damping and short-lived waves such as Pi2 pulsations. This detection algorithm neglects the events whose peak-to-peak amplitudes given by the wavelet coefficients are less than 0.6 nT. Our wavelet analysis detects not only Pi2 but also Pc3 and Pc4 pulsations on the dayside. According to Nosé *et al.* (1998), the rate of successful detection of Pi2 pulsation is more than 80% for the nightside (18–06 MLT). In particular, it is more than 90% around the local midnight (20–04 MLT). On the other hand, it is less than 30% on the dayside (06–18 MLT). Therefore we have analyzed the events detected only on the nightside (18–06 LT). The number of selected events is 480 at KAK, 304 at CZT, and 504 at PAF.

3. Analysis and Results

3.1 Mid-latitude Pi2 pulsations

We analyzed the Pi2 pulsations with the maximum entropy method (MEM) to obtain the spectra. In this analysis, a spectrum is estimated from an interval for 300 seconds, and the number of the MEM coefficients is fixed to 32. The dominant frequency is obtained by taking the peak of the spectral density. The upper panel of Fig. 1 shows an example of Pi2 pulsation detected at PAF during 17:10–17:30 UT on May 19, 1985, and the lower panel shows the power spectra of the Pi2 event at 17:17–17:22 UT. In this example the dominant frequencies are 14 and 13 mHz for H and D components, respectively.

The same analysis is carried out for each event at each station. Figure 2 shows the relation between local time and the dominant frequencies of Pi2 pulsations observed at PAF in 1984 and 1985. These events are classified by the Kp index. In this classification, the levels with minus or plus designations are included in the levels with no designations. For example, the case of Kp = 3 includes the geomagnetic condition of Kp = 3−, 3, 3+. Each symbol corresponds to the geomagnetic activity level measured by the Kp index as indicated in Fig. 2. The open symbols represent quiet conditions (Kp $\leq$ 3), and the filled symbols represent disturbed conditions (Kp $\geq$ 4). The upper and lower panels are for the H and D components, respectively. Although it is not so clear, the frequency under the disturbed conditions is higher than that under the quiet conditions at any local time. The frequency of Pi2 pulsations seems to be higher on the dawn side than that on the dusk side. In order to verify this, we calculated the averages of the dominant frequency at each local time bin. Figure 3 shows the averages of the dominant frequency of Pi2 pulsations in one hour local time period centered at every hour. Each line corresponds to the geomagnetic activity measured by the Kp index. Because of small number of the events, the average frequency is not presented for Kp $\geq$ 5. Two characteristics of the Pi2 frequency are found in these figures. One is the local time dependence of the frequency. On the dusk side, the frequencies of Pi2 pulsations are lower than those on the dawn side. The other is the dependence on the geomagnetic activity. The frequencies are lower in the case of low Kp, and they increase with increasing geomagnetic activity.

The Pi2 frequency at CZT is shown in Fig. 4 in the same format as Fig. 3. The frequency at CZT has a peak at 03 LT. However the frequency is constant with local time during the very quiet periods (Kp = 1). The frequencies of Pi2 pulsations at CZT also increase with increasing the geomagnetic activity.

3.2 Low-latitude Pi2 pulsations

The local time dependence of Pi2 frequency at KAK is shown in Fig. 5. Pi2 pulsations at KAK tend to have higher frequency in post-midnight than that in pre-midnight, and have a peak at 03–04 LT under the disturbed condition. The frequency is almost constant with local time during very quiet periods (Kp = 1). Similar Kp dependence to that at PAF and CZT is seen also at KAK. The frequency is higher under the disturbed condition than that under the quiet

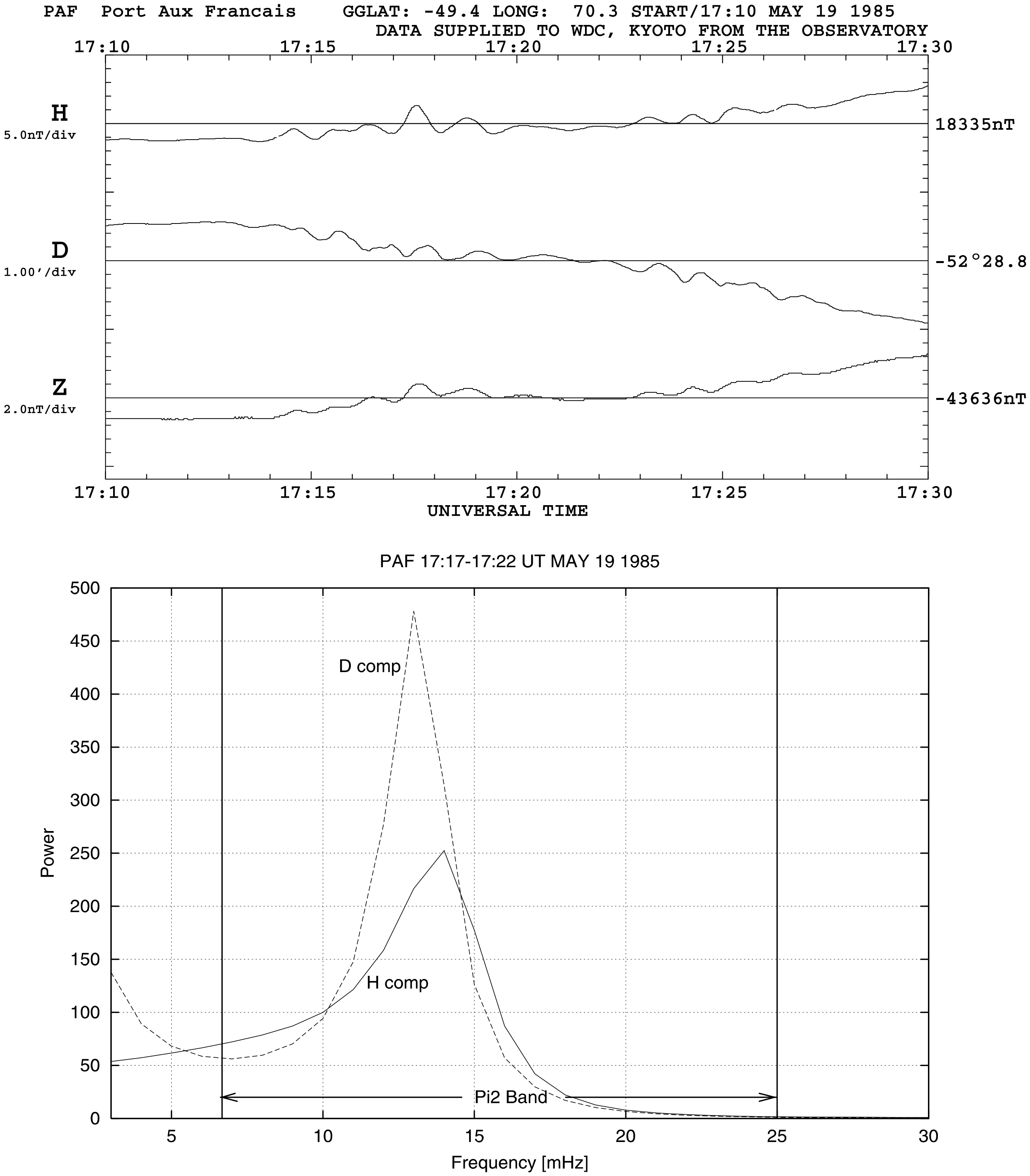


Fig. 1. The upper panel shows the magnetic field data at Port Aux Français (PAF) for 17:10–17:30 UT on May 19, 1985. The lower panel shows the power spectra of the Pi2 event at 17:17–17:22 UT. The dominant frequency is defined as the maximum of the spectrum. In this event the dominant frequencies are 14 and 13 mHz in the H and D components, respectively.

condition. The average frequency of Pi2 pulsation at KAK is higher than that at PAF. This may imply that the generation mechanisms are different between PAF and KAK.

The local time dependence at KAK is different from that at PAF, while it is similar to that at CZT. These results suggest that there is an excitation mechanism localized around the latitude of PAF, and that Pi2 pulsations at CZT and KAK have a different generation mechanism from that at PAF. These characteristics can be explained by taking into account the structure of the plasmapause as discussed in the next section.

4. Discussion

We found a local time dependence of Pi2 frequencies in mid- and low-latitudes as shown in the previous section. In addition, it is found that the averaged frequency is differ-

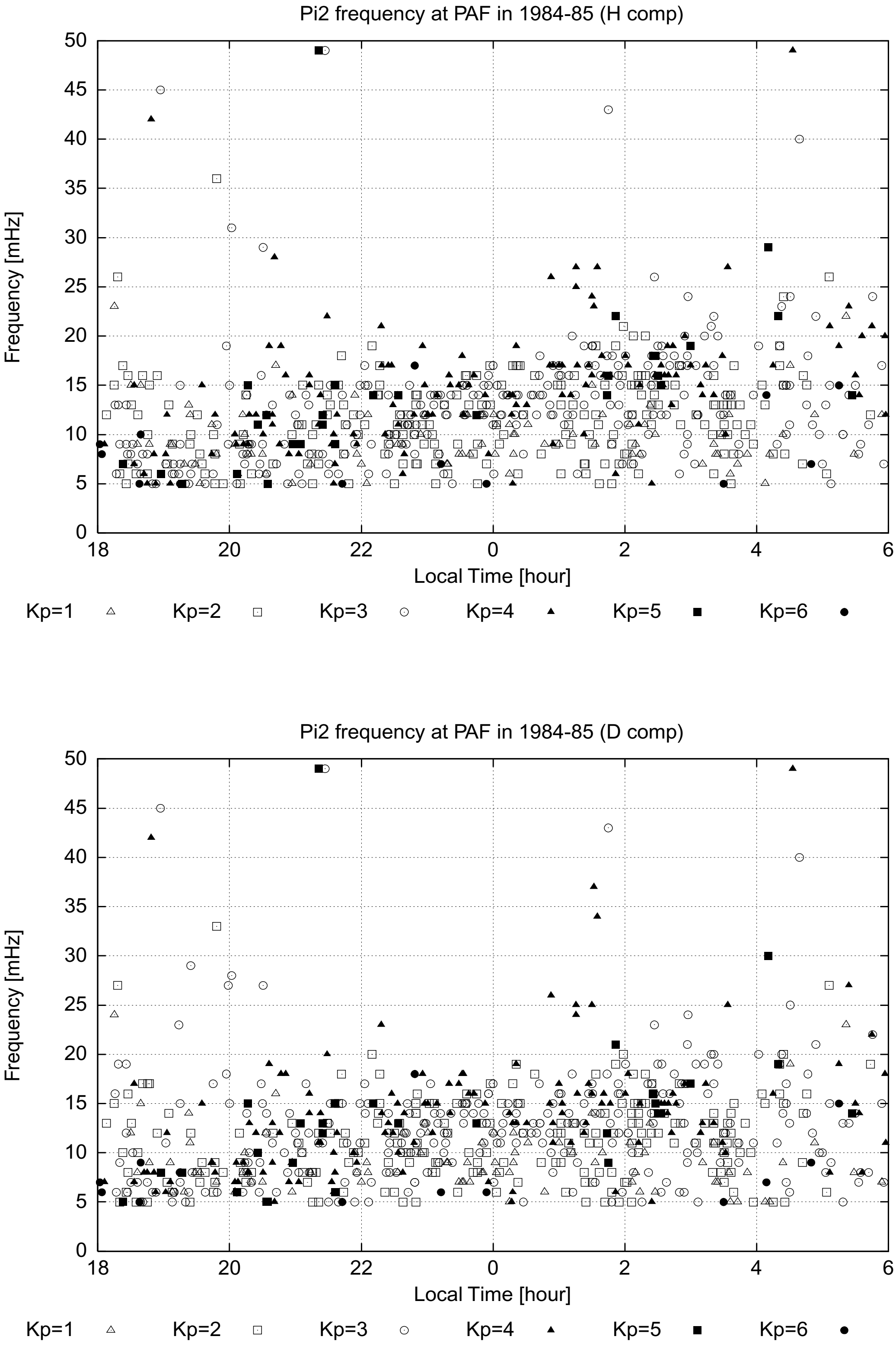


Fig. 2. Relation between local time and the dominant frequencies of Pi2 pulsations observed at PAF. The upper and lower panels show the dominant frequency in the H and D components, respectively. The geomagnetic activities for each event are distinguished with the different symbols indicated in the panel.

ent for mid- and low-latitudes. These results suggest that the cavity resonance is not the dominant mechanism for Pi2 pulsations at mid-latitudes. If the plasmaspheric cavity resonance is the dominant mechanism, the frequencies of Pi2 pulsations should be uniform in any local time sector at mid- and low-latitudes.

The mid-latitude Pi2 frequency should have the local time and Kp dependence if the surface wave is the dominant mechanism of Pi2 pulsations at mid-latitudes. The shape and the size of the plasmasphere can affect the period of the sur-

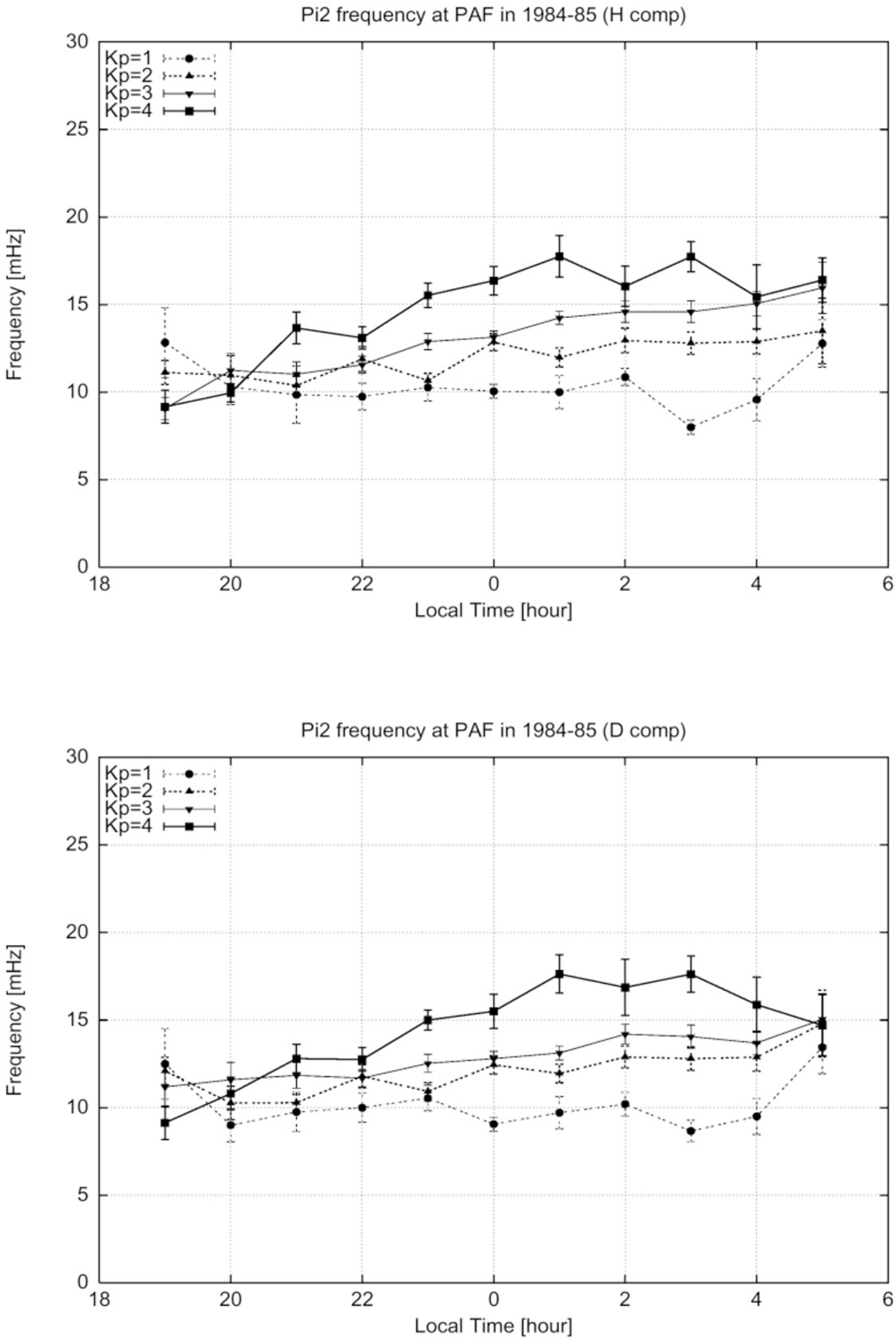
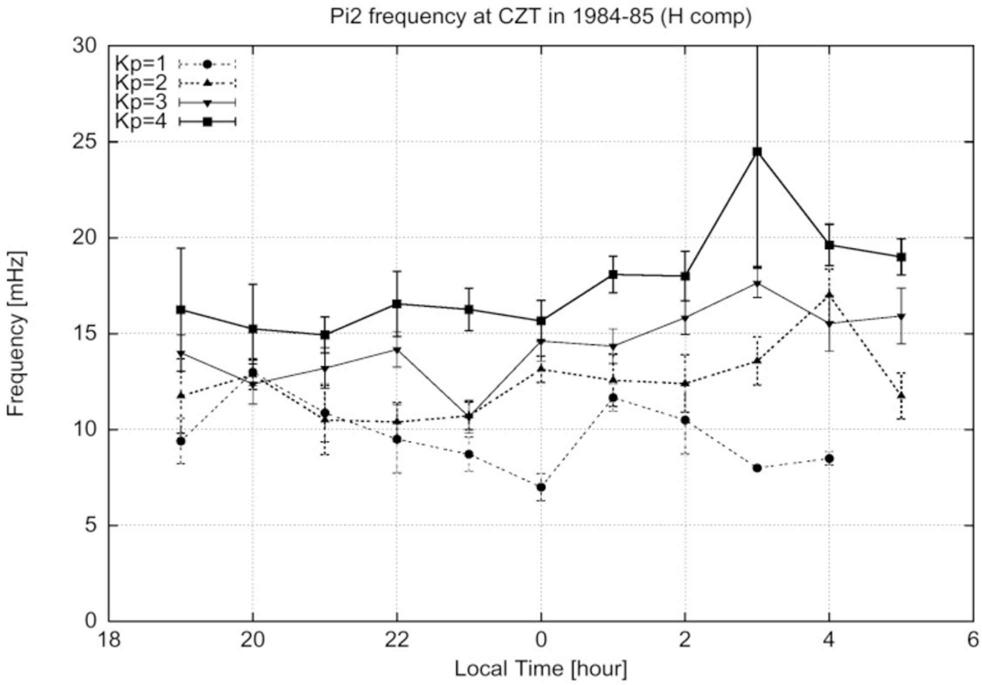


Fig. 3. Relation between local time and the dominant frequency of Pi2 pulsations observed at PAF. The upper panel shows the variation in the H component, and the lower panel shows that in the D component. The symbols indicate the average frequency, and the error bars are the standard error. Each line corresponds to the geomagnetic activity measured by Kp index as indicated in each panel.

face wave. The plasmasphere bulges out to the dusk side (e.g., Carpenter, 1966), and the field line length between magnetic conjugate points at the plasmapause is longer on the dusk side than that on the dawn side. Therefore the period of the surface wave on the plasmapause is expected to be longer on the dusk side than that on the dawn side. That is, the shape of the plasmapause can cause the local time dependence of the frequency of Pi2 pulsations.

We confirmed that the frequencies depend on the geomagnetic activity as has been reported by Saito *et al.* (1976). The Pi2 frequency is higher for higher Kp. This can be explained as the effect of the shrinkage of the plasmasphere under geomagnetic disturbed condition (e.g., Carpenter and Anderson, 1992). The field line on the plasmapause is shorter in disturbed period than that in quite period. Therefore the surface wave frequency is higher in the case of higher Kp.



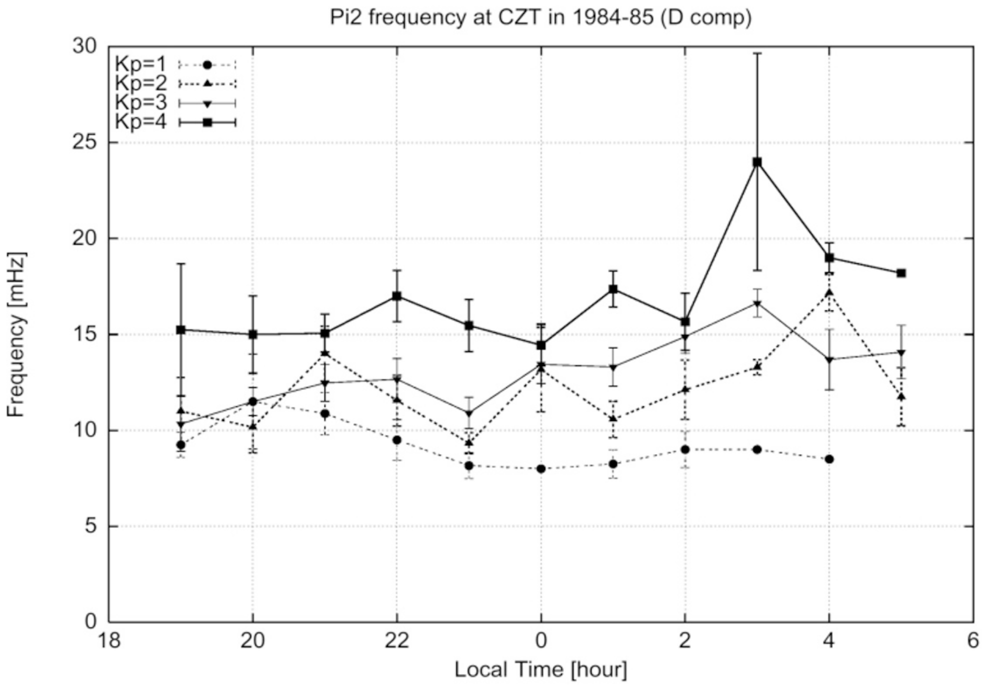


Fig. 4. Relation between local time and the frequencies of Pi2 pulsations observed at Crozet (CZT). The format is the same as Fig. 3.

The local time dependence of the Pi2 frequency is not clear at PAF under very quiet condition (Kp = 1), during which L-value of the plasmapause is expected to be much larger than that of PAF (L = 3.4). The Pi2 frequency at KAK seems to have weak dependence on local time for the quiet period. The situation is similar to the case of PAF during the quiet periods. These results suggest that the local time dependence can be seen only near the latitude of the plasmapause and that the surface wave on the plasmapause is the dominant mechanism of Pi2 pulsations observed at mid-latitudes.

In the plasmasphere, the electron density is higher on the dusk side than that on the dawn side (e.g., Tarcsai, 1985; Moore *et al.*, 1987). The frequency of the field line resonance is lower on the high density side than that on the low density side. Therefore the frequency of the local field line resonance might have a local time dependence which is also consistent qualitatively with observations. However, the lo-

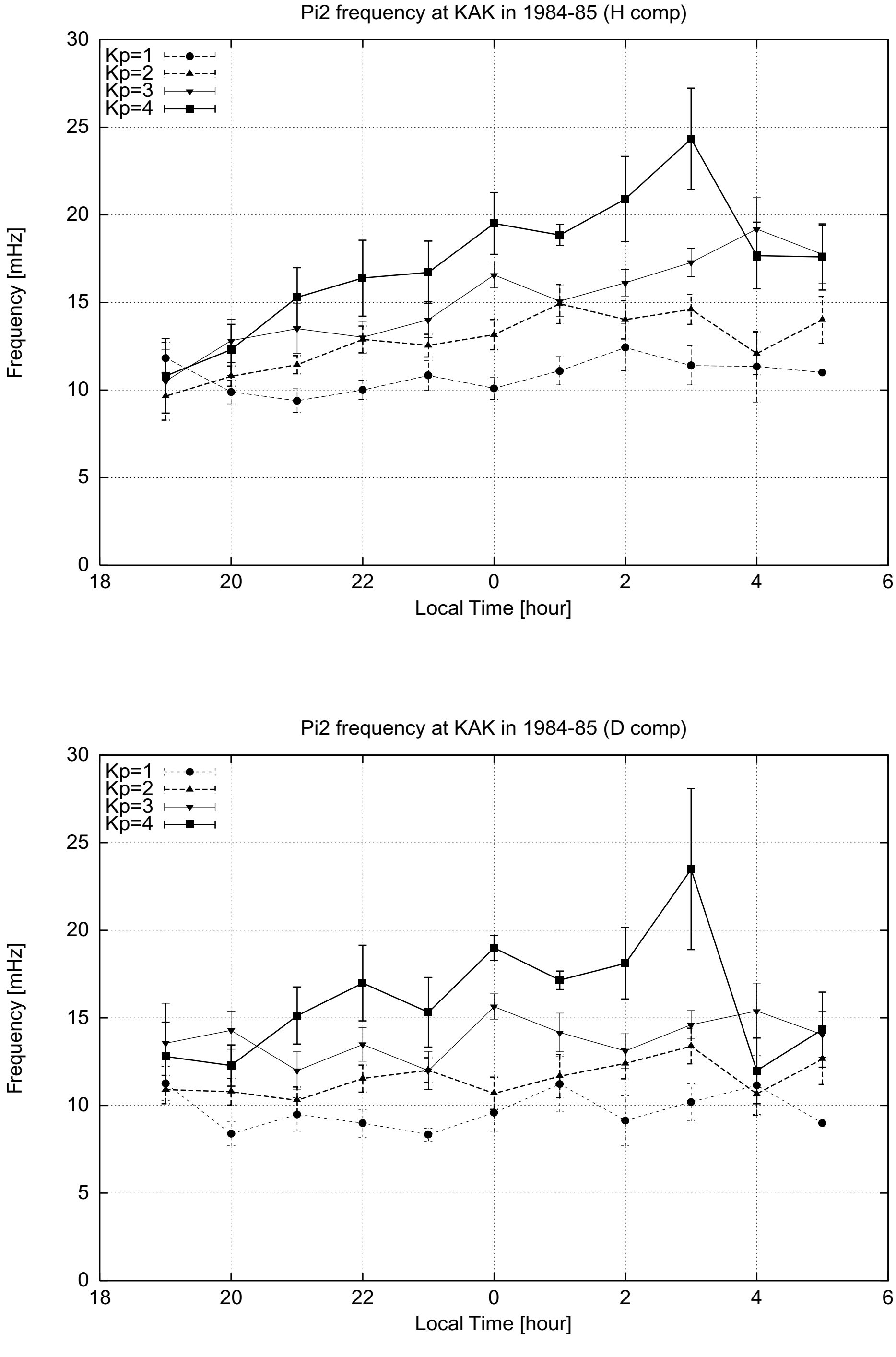


Fig. 5. Relation between local time and the frequencies of Pi2 pulsations observed at Kakioka (KAK). The format is the same as Fig. 3.

cal FLR cannot explain the Kp dependence of the Pi2 frequency. In the inner magnetosphere, the magnetic field line length can be almost constant to the geomagnetic activity. Because O^+ would come up in the plasmasphere under geomagnetically disturbed conditions (Young *et al.*, 1982) and increase the mass density, the local FLR may have lower frequency under disturbed conditions than that under quiet conditions. This tendency is not consistent with observations. This suggests that the local field line resonance is not the dominant mechanism of the mid-latitude Pi2 pulsations.

We estimated the resonance frequency of the surface wave using the global core plasma model (GCPM) (Gallagher *et al.*, 2000). The GCPM provides the core plasma density as a function of geomagnetic and solar conditions. A blunt plasmaspheric bulge and rotation of the bulge with changing geomagnetic conditions are included in the model. According to Chen and Hasegawa (1974), the period of the surface wave on the plasmapause, T_s, is given as follow;

$$T_s = 2 \int \frac{ds}{\sqrt{2} V_A}, \tag{1}$$

where the integration is carried out between the conjugate ionospheres along a given field line, and V_A is the Alfvén velocity in the high density side of the discontinuity. The local magnetic strength, B, is written as $B = B_0\sqrt{1 + 3\sin^2\lambda}/r^3$, where r is the radial distance with a unit of the Earth radius, λ is the dipole latitude in radian and B_0 is an equatorial geomagnetic force at $r = 1$. B_0 is assumed to be 30000 (nT). In this estimation, the proton number density is assumed to be equal to the electron number density. Previous studies on the plasma density variation along magnetic L shell have seen little variation with latitude (e.g., Decreau *et al.*, 1986). Therefore we assume that the density in the plasmasphere and on the plasmapause is constant along magnetic L shell. Gallagher *et al.* (2000) proposed a model of the local electron number density distribution, n_e, which is expressed as

$$n_e = 10^{g \cdot h} - 1. \tag{2}$$

The function g which is obtained from Carpenter and Anderson (1992) is expressed as a function of the L, the day of the year and the 13-month-average sunspot number, $\bar{R}$. To compare the theoretical frequency with the averaged frequencies of Pi2 pulsations detected in two years, we neglected the part of the day of the year. The modified function g is expressed as

$$g = (-0.3145\mathrm{L} + 3.9043) + [0.00127\bar{R} - 0.0635]e^{(-\frac{\mathrm{L}-2}{1.5})}. \tag{3}$$

We took $\bar{R} = 20$ which is a typical value for the period 1984 to 1985. The function h is obtained by Gallagher *et al.* (2000), and we used the function with no modification. According to Carpenter and Anderson (1992), the average plasmapause location is given in the form of

$$L_{pp} = 5.6 - 0.46K_{Pmax}, \tag{4}$$

where K_{Pmax} is the maximum Kp value for the proceeding 24-hours. To include the effect of the plasmaspheric bulge, the equation (4) are modified in GCPM as

$$\mathrm{L}_{pp} = (5.6 - 0.46K_{Pmax})[1 + e^{(-1.5x^2)+0.08x-0.7}], \tag{5}$$

where x is the azimuthal angle relative to the bulge centroid in radians. The center of the plasmaspheric bulge is expressed as

$$\Phi_B(\text{hours}) = \frac{47}{\mathrm{K_P} + 3.9} + 11.3. \tag{6}$$

Figure 6 shows the location of the plasmapause for Kp = 1, 3, and 5 using the GCPM. This figure shows that the plasmaspheric bulge rotates to sunward and the plasmasphere shrinks for higher geomagnetic activity.

The result of the model calculation and comparison with our data analysis for Kp = 1–4 are shown in Figs. 7(a)–(d). Figure 7(a) shows the relation between the result of the observed data analysis at PAF and the estimated frequency of the surface mode wave for Kp = 1. Figures 7(b), (c), and (d) show the relation when the Kp index is 2, 3, and 4, respectively. The square and circle indicate the average frequency of H and D components of Pi2 pulsations at each local time, respectively. The circles are put at slightly earlier local time than the actual local time to avoid the overlapping of the symbols. The solid error bars indicate the standard errors for the averaged frequencies in the H component and the dashed error bars indicate those in the D component. The curved line indicates the theoretically estimated frequency of the surface wave. At Kp = 1–3, the results of data analysis are roughly consistent with the model estimation. In the case of Kp = 4, there is some difference in the absolute value of the frequency between the observations and the model estimation, but the local time dependence in the model estimation is consistent with that in the observations. We will discuss later what causes this difference. These results strongly suggest that the period of the mid-latitude Pi2 pulsation is determined by the surface wave on the plasmapause.

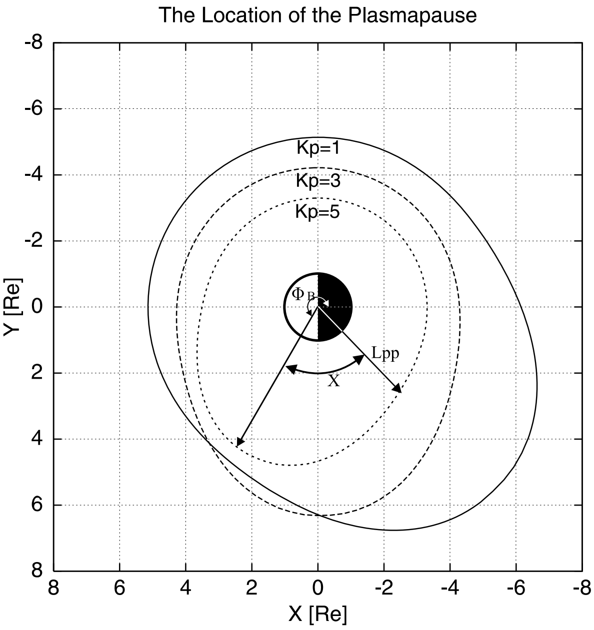


Fig. 6. Location of the plasmapause for the level of the geomagnetic activity corresponding to Kp = 1, 3, and 5 in GSM coordinates. The solid, long-dashed, and short-dashed line indicate the position of the plasmapause with local time for Kp = 1, 3, and 5, respectively. The circle in the center represents the Earth (L = 1 Re). Φ_B represents the local time of the plasmaspheric bulge center in hours. x is the azimuthal angle relative to the bulge centroid in the radians.

The local time dependence of the dominant frequency at KAK is different from that at PAF. A clear local time dependence can be found in both the H and D components at PAF where the foot point of the plasmapause is closer than that at KAK. Such local time variation of the frequency is not found at KAK during the quiet periods. Figure 8 shows a comparison of the estimation with the data analysis for KAK. The format is the same as that in Fig. 7. The average frequency of Pi2 pulsations at PAF for the H component is nealy equal to that for the D component. On the other hand, the average frequency of Pi2 pulsations at KAK is different between the H and D components. This suggests that the dominant mechanism of Pi2 pulsations at KAK is different from that at PAF. That is, the surface wave may not be the dominant mechanism at low-latitudes, and the effect from the surface wave on the plasmapause is detected only near the foot point of the plasmapause.

The frequency of the surface wave at high Kp calculated with the plasmaspheric model is different from the frequency we obtained from data analysis. The estimated frequency is

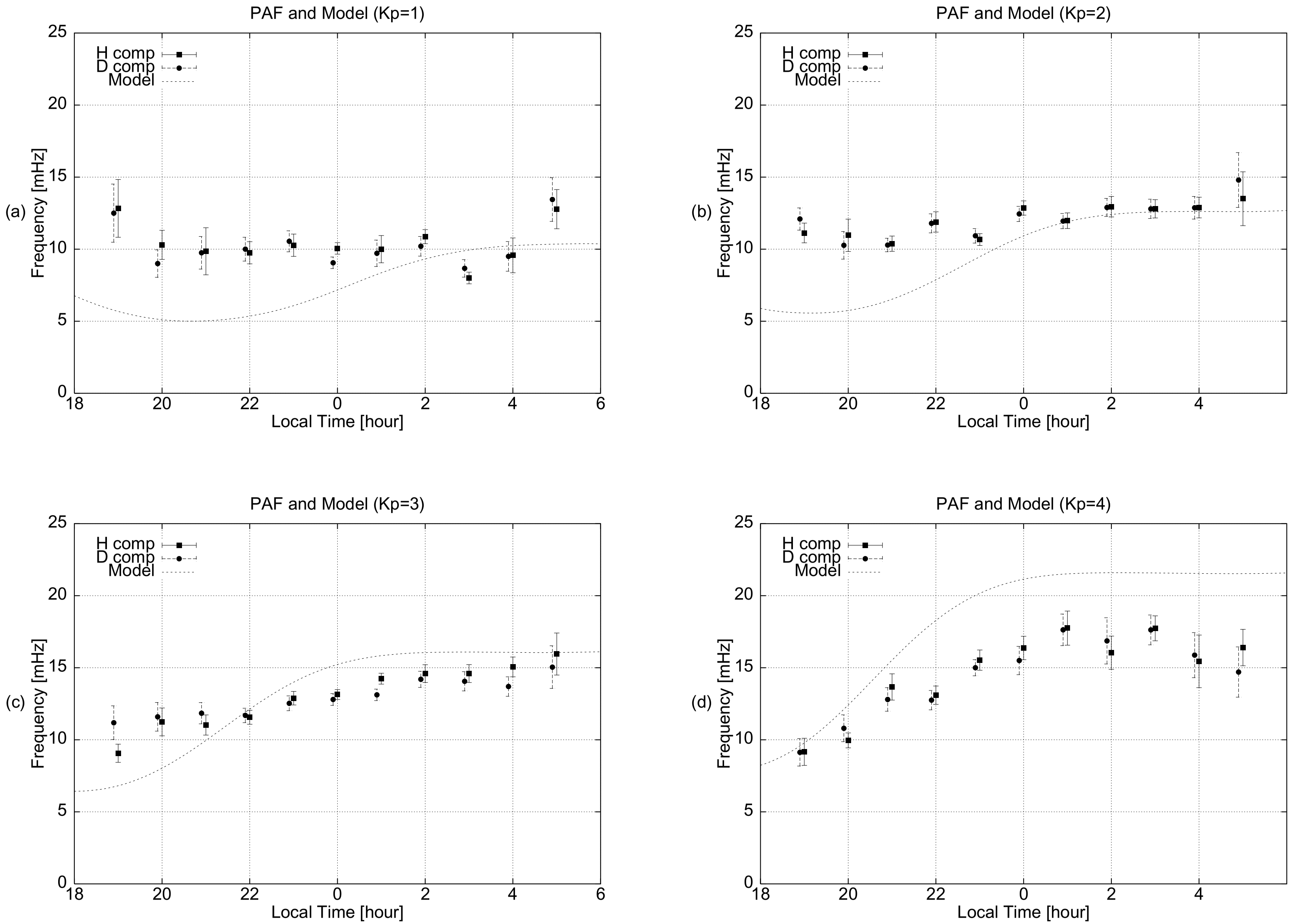


Fig. 7. A comparison between the local time dependence of the frequency of Pi2 pulsation at PAF and the theoretical frequency of the surface wave. Panels (a), (b), (c), and (d) show the relation for Kp = 1, 2, 3 and 4, respectively. The square and circle symbols indicate the average frequency of H and D components of Pi2 pulsations in each local time, respectively. The solid lines show the error bars of the Pi2 frequency for H component. The dashed lines show the error bars of the Pi2 frequency for D component. The curved line indicates the theoretical frequency of the surface wave.

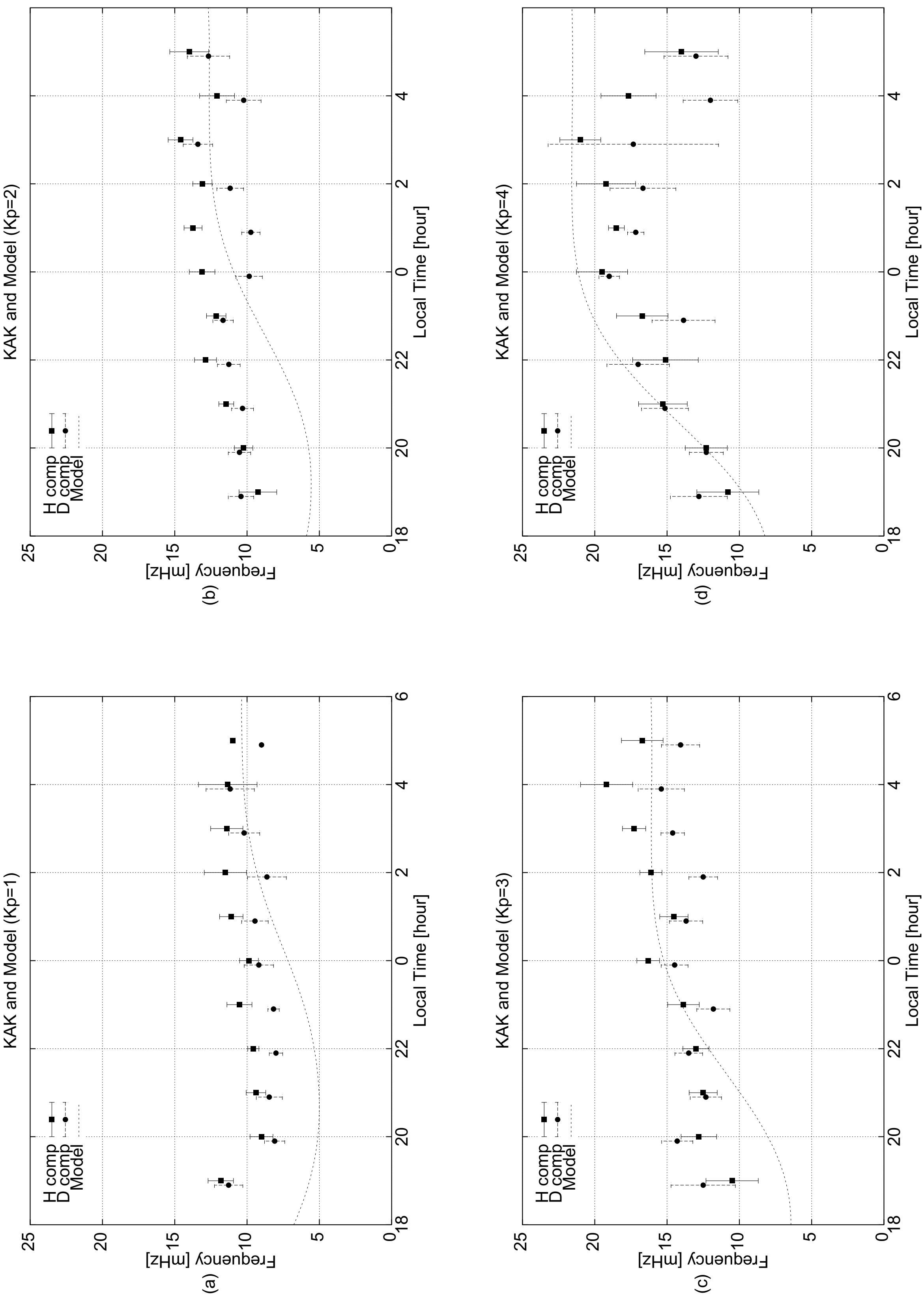


Fig. 8. A comparison between the local time dependence of the frequency of Pi2 pulsation at KAK and the theoretical frequency of the surface wave. The format is the same as Fig. 7.

higher than that obtained from the observations. We used the GCPM which expresses the average plasmapause location. This model seems to be adequate at low Kp, but at high Kp, it might have a problem. Figure 7 of Chappell *et al.* (1970) showed that the Kp dependence of the plasmapause position is not linear for all Kp, and at high Kp, the coefficient of Kp in Eq. (5) could be too small. There is a good possibility that O^+ ions come up to the plasmapause in the geomagnetically disturbed condition (Young *et al.*, 1982). When the ratio of O^+ increases, the Alfvén velocity becomes smaller than that in the quiet condition. Then the frequency of the surface wave is lower in the disturbed condition than that of the estimated frequency.

We summarize that the dominant frequency of mid-latitude Pi2 pulsations has a local time dependence, which supposed to be caused by the structure of the plasmapause. It is plausible that the dominant mechanism of Pi2 pulsation at mid-latitudes is the surface wave on the plasmapause. However there remain some questions. The observed frequency decreases on the dawn side at CZT and KAK. The frequency of Pi2 pulsation at KAK on the dusk and dawn sides has almost no dependence on the geomagnetic activity. Further study is needed in order to make these points clear.

The surface wave couples with the Alfvén mode wave if m-number is not zero. Since the Alfvén mode wave forms FLR, the FLR signature might be expected around the footprint of the plasmapause. From a numerical simulation, Fujita *et al.* (2002) found the FLR signature at the plasmapause latitude. However, our study showed that the observed periods of Pi2s are consistent with the periods of surface wave rather than those of FLR. (The periods of surface wave are $\sqrt{2}$ times shorter than those of FLR, as shown in Eq. (1).) To interpret this discrepancy, one might be able to think that the observed Pi2s had $m \sim 0$, resulting in no coupling with the Alfvén waves, or that FLR was exited at latitudes different from the plasmapause latitude in the actual magnetosphere. In future study we need to examine the latitudinal variation of the wave around the plasmapause.

Another point to be examined in future study is a comparison of the results shown in this paper with those of a theoretical calculation of plasmaspheric cavity resonance mode. No numerical simulation of the cavity mode with MLT dependent plasmaspheric model has been done so far.

The results shown in this paper are obtained by a statistical analysis using only 3 stations. Therefore it would be necessary to examine the MLT dependence for each event with the data simultaneously obtained from longitudinal chain of geomagnetic stations located in mid-latitudes to confirm the results shown here.

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