Spectral and Polarization Characteristics of Pc 3–5 Magnetic Pulsations Observed at the Syowa Station-Iceland Conjugate Pair

Miyoko IWABUCHI*, Hiroshi FUKUNISHI* and Natsuo SATO*

昭和基地—アイスラント地磁気共役点て観測された Pc 3–5 型脈動のスペクトルおよび偏波特性

岩渕美代子*・福西　浩*・佐藤夏雄*

要旨　1977 年 7 月 29 日—9 月 18 日まて 52 日間にわたってアイスラントフサヘルおよび南極昭和，みずほ基地て観測された地磁気脈動テータの解析から以下のことが明らかになった

(1) 中心周波数か，20–40 mHz および 4–8 mHz の 2 つのバントが，昼間観測される　(2) *f–t* スペクトルの構造は，共役点で非常に類似している．(3) これら脈動の位相は，共役点て *H* 成分か in-phase, *D* 成分が out-of-phase の関係を示す　(4) *H–D* 平面における楕円偏波の主軸の向きは，12 MLT を境に反転する

これらの結果から昼間の Pc 3–5 脈動は，磁気圏，境界面またはその外側てつくり出された MHD 波動が，磁気圏内に伝わり磁力線の odd-mode standing oscillation を励起させたものと考えられる．

***Abstract*:** From the magnetic pulsation data recorded at the Syowa Station-Iceland conjugate pair, it is found that there are at least two pulsation bands in the Pc 3–5 frequency range in the daytime. One pulsation band occurs in the 20–40 mHz range, while the other band occurs in the 4–8 mHz range, often independently of the 20–40 mHz band The *f–t* spectral patterns of these pulsations are quite similar at the conjugate points, with the wave phase characteristics of odd-mode standing oscillations of local magnetic field lines It is also found that the orientation angles of the polarization ellipses in the *H–D* plane switch across the magnetic local noon. These results suggest that the 20–40 mHz band and the 4–8 mHz band are standing oscillations of resonant field lines excited by external driving forces such as the Kelvin-Helmholtz instability on the magnetopause and/or the MHD waves generated near the bow shock

1. Introduction

Magnetic pulsations in the Pc 3–5 frequency range (~2–100 mHz) were interpreted in terms of standing resonances of the earth's magnetic field lines (DUNGEY,

* 国立極地研究所. National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173

1954; OBAYASHI and JACOBS, 1958; RADOSKI and CAROVILLANO, 1966; RADOSKI, 1966) or resonances of geomagnetic cavity as a whole (OBAYASHI, 1958; MCCLAY, 1970). These two basic resonance modes correspond to the shear Alfvén (anisotropic) and magnetosonic (isotropic) waves. However, the cavity or the field line resonance ideas fail to explain the recent experimental results obtained from the network of magnetometer stations. For example, they can not explain a switch in the sense of polarization on each side of the latitude where peak amplitude is observed (SAMSON *et al.*, 1971; LANZEROTTI *et al.*, 1974a) and also a switch of polarization sense across local noon (SAMSON *et al.*, 1971; FUKUNISHI *et al.*, 1975; LANZEROTTI *et al.*, 1976; OLSON and ROSTOKER, 1978). These polarization characteristics of long-period pulsations have been well explained by a coupling of resonant field lines to Kelvin-Helmholtz generated surface waves on the magnetopause (SOUTHWOOD, 1974; CHEN and HASEGAWA, 1974).

The excitation mechanisms of MHD waves in the magnetosphere can be discussed in detail if the wave number vectors of magnetic pulsations are found. The radial and longitudinal wave numbers were estimated from wave phase differences between magnetometer stations arrayed in latitude (SAMSON and ROSTOKER, 1972; ORR, 1973; LANZEROTTI *et al.*, 1974a; LAM and ROSTOKER, 1978) and in longitude (GREEN 1976; BARKER *et al.*, 1977; OLSON and ROSTOKER, 1978), and also from the phase measurements made between multiple spacecraft in the magnetosphere (HUGHES *et al.*, 1978). On the other hand, the wave number along the geomagnetic field lines can be estimated by using data obtained from observations at magnetic conjugate points (*e.g.*, SUGIURA and WILSON, 1964; LANZEROTTI and FUKUNISHI, 1974), and ground/satellite correlative measurements (*e.g*, LANZEROTTI *et al.*, 1974b; KOKUBUN *et al.*, 1976). The measurements of magnetic pulsations at conjugate points can also give evidences for the global extent of magnetic pulsations from the coherency analysis. The conjugate data are useful for the study of the ionospheric effects on MHD waves because the electron density profile in the ionosphere is generally different at conjugate regions. However, up to the present available conjugate data are greatly limited because of coarse network of magnetometer stations in the southern hemisphere, particularly in the southern polar region.

Conjugacies of Pc 3–5 and Pi 2 pulsations near $L=4$ were studied in detail by using pulsation data recorded at Siple in Antarctica and the meridian chain stations in the conjugate area of Siple (LANZEROTTI *et al.*, 1972; FUKUNISHI and LANZEROTTI, 1974; FUKUNISHI, 1975a; FUKUNISHI *et al.*, 1975). They found that the H component oscillates almost in phase, while the D component oscillates almost out-of-phase at the conjugate points in the most cases of the observed pulsation events. The result suggests that Pc 3–5 and Pi 2 pulsations observed near $L=4$ are in general characterized by odd-mode standing oscillations of local resonant field lines (*c.f.* SUGIURA and

WILSON, 1964; LANZEROTTI and FUKUNISHI, 1974). The similar wave phase relation of Pc 3 pulsations at the Sogra-Kerguelen conjugate pair (L=3.6) were presented in the work of VAN-CHI *et al.*, (1968). The conjugacy of Pi 2 pulsations near L=4 was also studied by using pulsation data recorded at the Halley Bay-St. Authony pair of conjugate points (STUART, 1975).

The wave phase relation of Pc 5 and Pg pulsations at the conjugate points in the auroral zone latitudes was studied by using pulsation data recorded at the College-Macquaire Island pair (SUGIURA and WILSON, 1964; WILSON, 1966; ANNEXSTAD and WILSON, 1968) and the Syowa Station-Reykjavik pair (NAGATA *et al*, 1963). However, only several typical magnetic pulsation events in the Pc 4–5 frequency range and with large amplitudes were analyzed in their works, because rapid-run magnetograms were available at that time. Therefore, as is summarized in the paper of LANZEROTTI and FUKUNISHI (1974), the conjugate phase relation in the auroral latitudes is not clear at present.

Observations of magnetic pulsations, ELF-VLF emissions, cosmic noise absorption, and auroras were carried out at Syowa and Mizuho Stations in Antarctica and at Husafell in Iceland which is located near the conjugate point of Syowa Station.

Table 1 Locations of Husafell, Syowa and Mizuho Stations in geographic and geomagnetic coordinates, L values and conjugate points of these stations

Station name	Geographic		Geomagnetic		L	Conjugate geographic	
	Latitude	Longitude	Latitude	Longitude		Latitude	Longitude
Husafell	64 7°N	20 9°W	70 2°	74 2°	6 14	68 9°S	40 1°E
Syowa	69 0°S	39 6°E	−70 0°	79 4°	6 02	64 3°N	21 2°W
Mizuho	70 7°S	44 3°W	−72 3°	80 6°	7 04	65 9°N	22 7°W

The geographic and geomagnetic coordinates, L values and the conjugate points of these stations are given in Table 1. The conjugate points were calculated from the 1975 international geomagnetic reference field (IGRF) model. The locations of Husafell and the conjugate points of Syowa and Mizuho Stations are also shown in Fig. 1. It is found that the Syowa Station conjugate point is located at a distance of ~50 km from Husafell. The magnetic local time of these stations is almost equal to universal time. This conjugate experiment was carried out under the joint research program between our institute and the GEOS S-300 experimenters (GENDRIN *et al.*, 1978). Magnetic pulsations were observed at Husafell for 52 days from July 29 to September 18, 1977. The footprints of magnetic field lines through GEOS-1 were located near the area covered by this station network during the observation period, as is shown in Fig. 1.

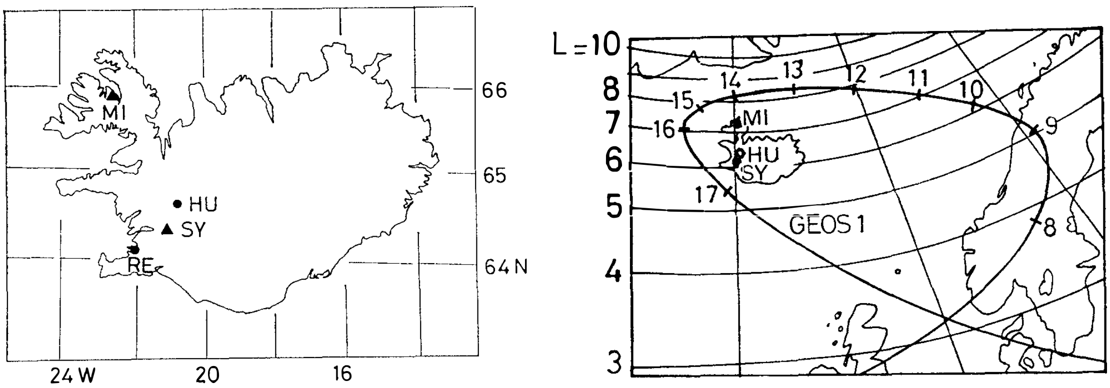

Fig 1 Locations of Husafell in Iceland and the conjugate points of Syowa and Mizuho Stations in Antarctica. The conjugate points are determined from the 1975 international geomagnetic reference field (IGRF) model. The footprint of the field line passing through GEOS-1 on August 16, 1977, labelled in UT, is given in the right pannel

Magnetic pulsations measured by induction magnetometers were recorded on analogue magnetic tapes. Using these analogue tapes, frequency-time spectra were made by means of a real-time FFT spectral analyzer. Then, the analogue tapes were converted to digital magnetic tapes with a sampling time of 0.6 sec, and dynamic cross-spectra of 1536 points (922 sec) were successively computed with overlapping points of 768 (461 sec). The cross-spectra were computed by the FFT method with Hamming data window. The calculated spectral elements are 1) power spectra of the H and D components at the three stations, 2) phase differences and coherencies between the H and D components at the three stations, 3) polarizations, major axis orientations and ellipticities in the H–D plane at the three stations, and 4) phase differences and coherencies of the H and D components between two stations. These spectral elements were averaged in the three period range of Pc 5 (600–150 sec), Pc 4 (150–45 sec) and Pc 3 (45–10 sec) and also in the time interval of one hour for the statistical study of wave characteristics of magnetic pulsations.

2. Frequency-Time Spectra of Magnetic Pulsations Observed near $L=6$

In general, two spectral bands are seen in the f–t spectra of magnetic pulsations observed at Syowa, Mizuho Stations and Husafell. One spectral band is usually seen in the Pc 3 frequency range (22–100 mHz) and another in the Pc 4–5 range (1.6–22 mHz). Fig. 2 shows typical examples of the spectral band in the Pc 3 range. It is apparent that the intensity of the Pc 3 band is greatly enhanced in the daytime, particularly in the time interval of 06–12 MLT. The distinct local time dependence is

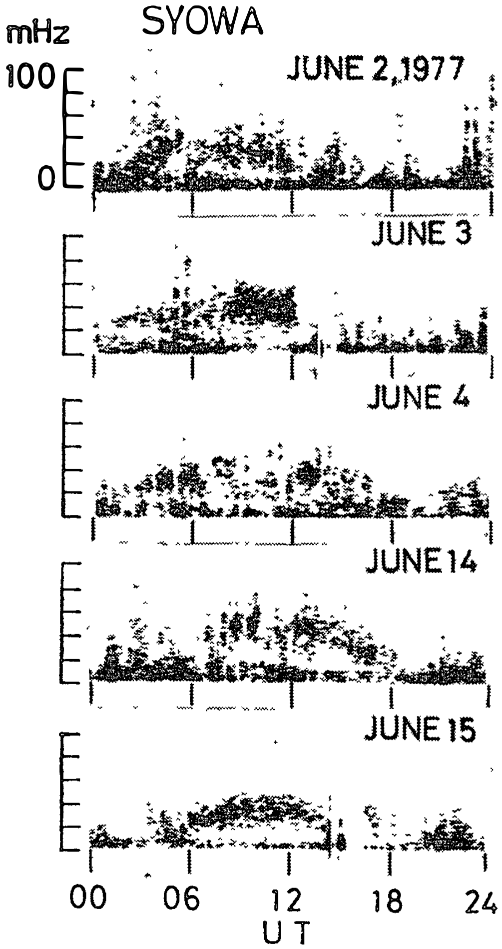

Fig 2 Examples of spectral bands in the Pc 3 frequency range. Universal time is almost equal to the magnetic local time at Syowa Station

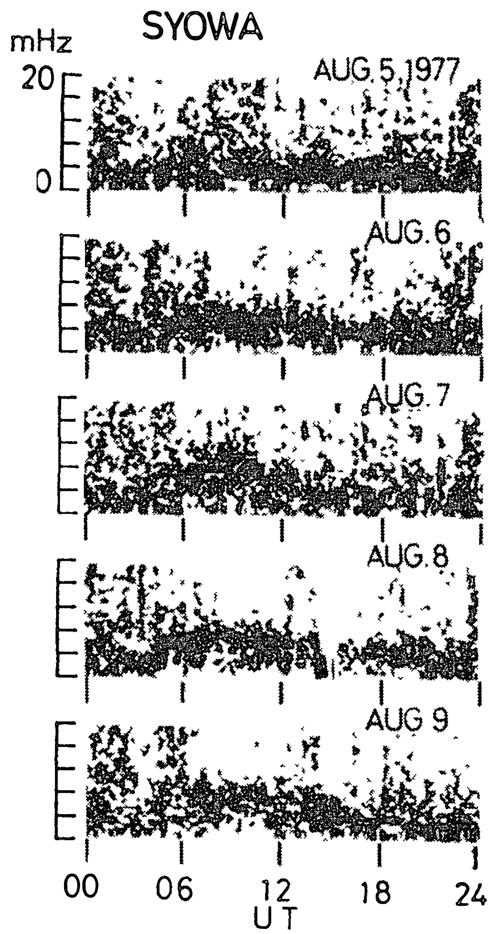

Fig 3 Examples of spectral bands in the Pc 4–5 frequency range at Syowa Station

found in the frequency of the Pc 3 band with a maximum frequency of ~40 mHz at 09–12 MLT and a minimum frequency of ~20 mHz at 15–18 MLT.

Examples of the spectral band in the Pc 4–5 frequency range are given in Fig. 3. This band is usually seen throughout the day, although the intensity of the band is enhanced during the daytime hours. The frequency of the spectral band shows also a clear diurnal variation with a maximum frequency of ~6–8 mHz at ~9 MLT and a minimum frequency of ~2–4 mHz in the nighttime It seems that the two pulsation bands presented in Figs 2 and 3 occur independently For example, it is found in Fig. 4 that the Pc 3 band appeared in the daytime every day, while the Pc 4–5 band was distinct only on June 20, 21, 23 and 24, 1977. The result suggests that there are at least two independent sources in the daytime for excitation of MHD waves at the auroral zone latitudes.

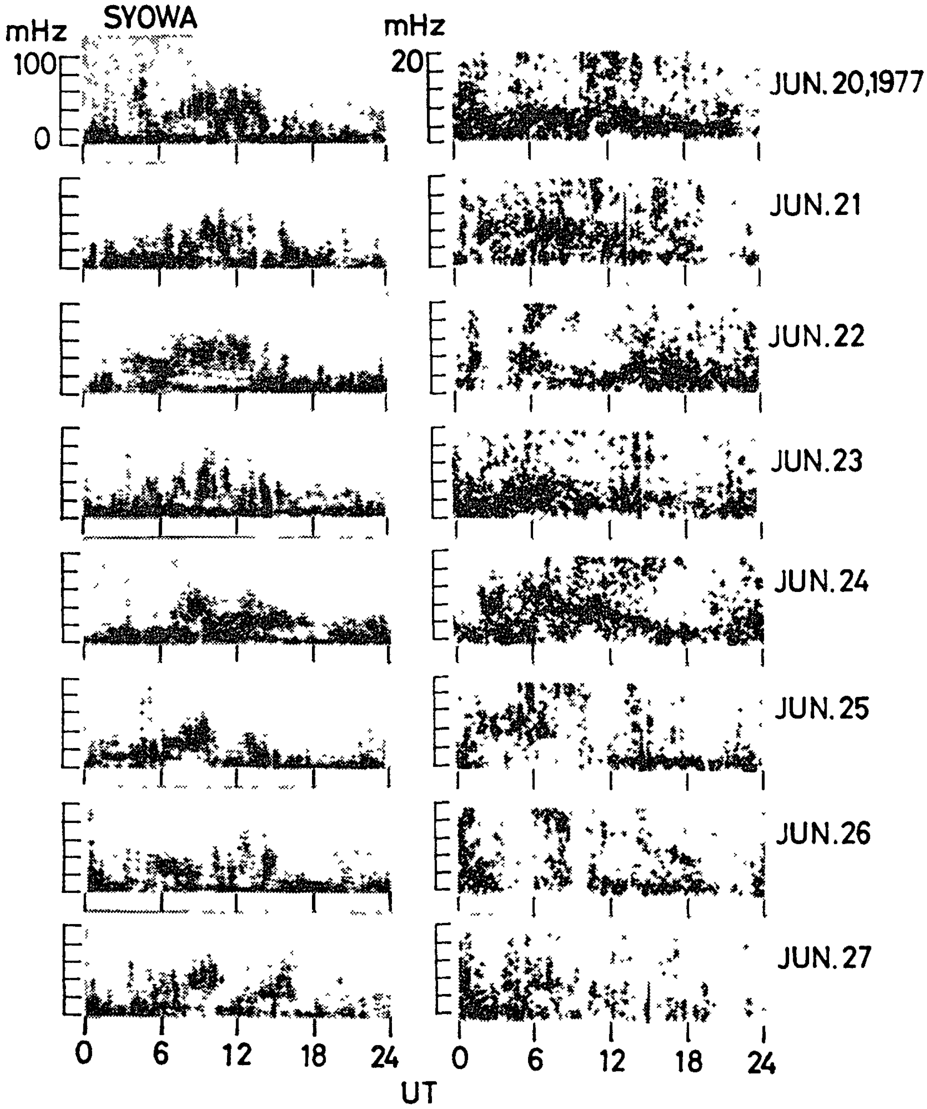

Fig 4. Successive frequency-time spectra in the two frequency ranges of 0–20 and 0–100 mHz from June 20 to June 27, 1977

3. Conjugacy of *f–t* Spectra in the Pc 3–5 Range

Examples of *f–t* spectra of magnetic pulsations recorded at the Syowa Station-Husafell conjugate pair are given in Figs. 5–7. It is found that two pulsation bands (5 mHz and 30 mHz bands) were excited on August 18 and 19, 1977, while only Pc 3 band with a center-frequency of $\sim$40 mHz was excited on September 3, 1977. A narrow spectral band which is seen in Fig. 7 around 10 mHz in the time interval 10–12 UT corresponds to Pg pulsation. These examples show that the spectral patterns of Pc 3, Pc 4–5 and Pg pulsations are quite similar to each other at the conjugate points,

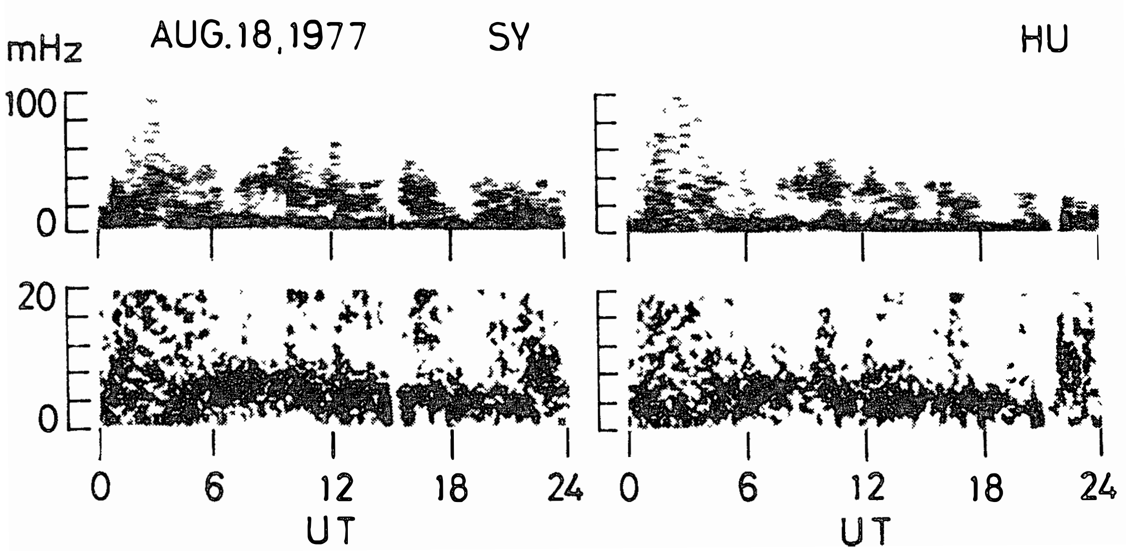

Fig. 5. Frequency-time spectra in the frequency ranges of 0–20 and 0–100 mHz recorded at Syowa Station and Husafell on August 18, 1977.

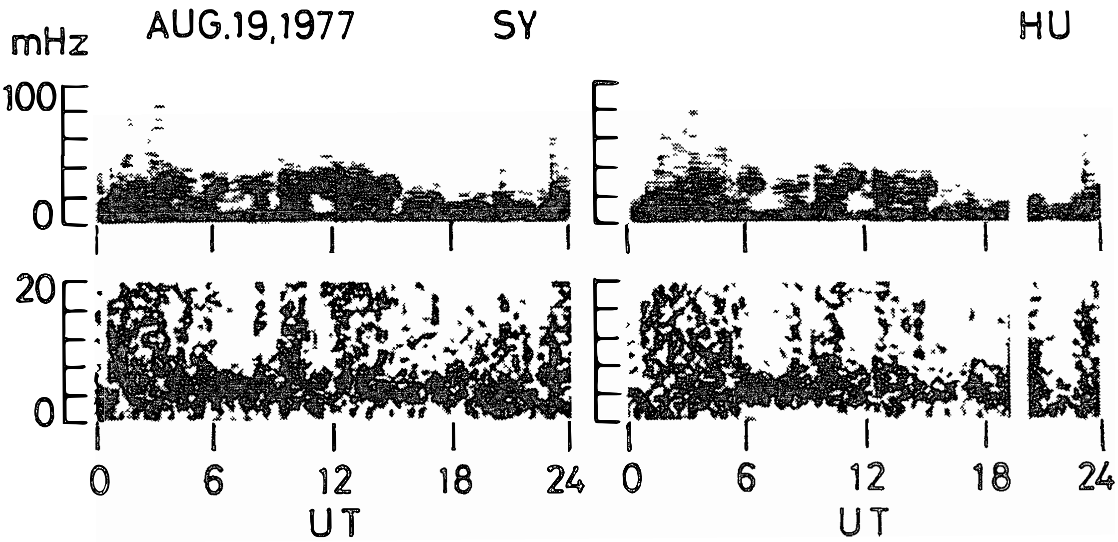

Fig. 6. Frequency-time spectra in the frequency ranges of 0–20 and 0–100 mHz recorded at Syowa Station and Husafell on August 19, 1977.

often even in their fine structures. It is also found in Figs. 5–7 that Pi pulsations in the nighttime with burst-like spectral structures occurred simultaneously at the conjugate pair.

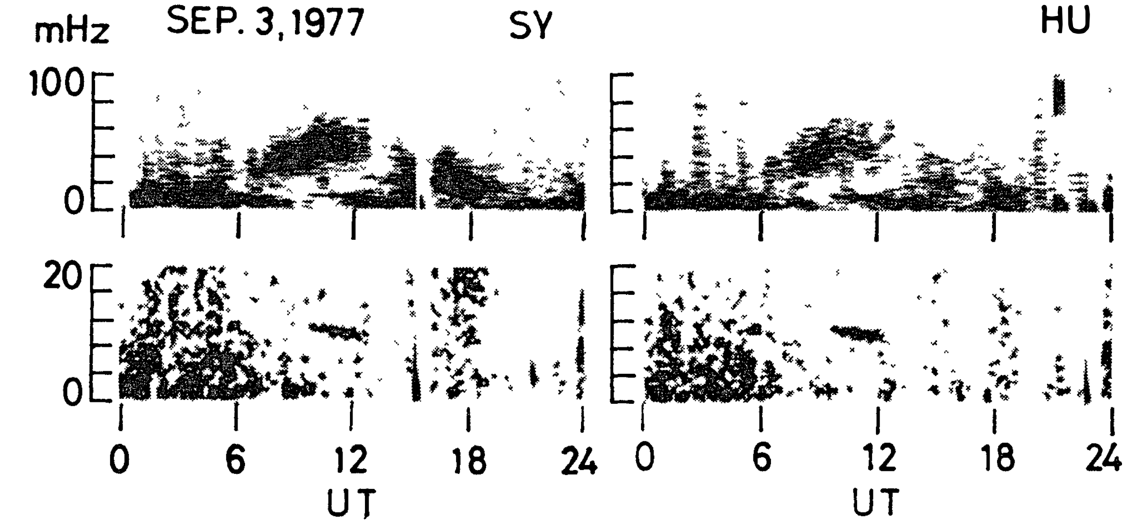

Fig. 7. Frequency-time spectra in the frequency ranges of 0–20 and 0–100 mHz recorded at Syowa Station and Husafell on September 3, 1977.

4. Diurnal Variation of the Hourly Total Powers in the Pc 3, 4 and 5 Bands

As is presented in Figs. 2–7, the frequency and the power intensity of the spectral bands in the Pc 3–5 range show significant diurnal variations. Plotted in Fig. 8 as a function of universal time on August 5, 1977, are the hourly total powers of the *H* components in the Pc 3, 4 and 5 bands. It is noted that the power in the Pc 5 band

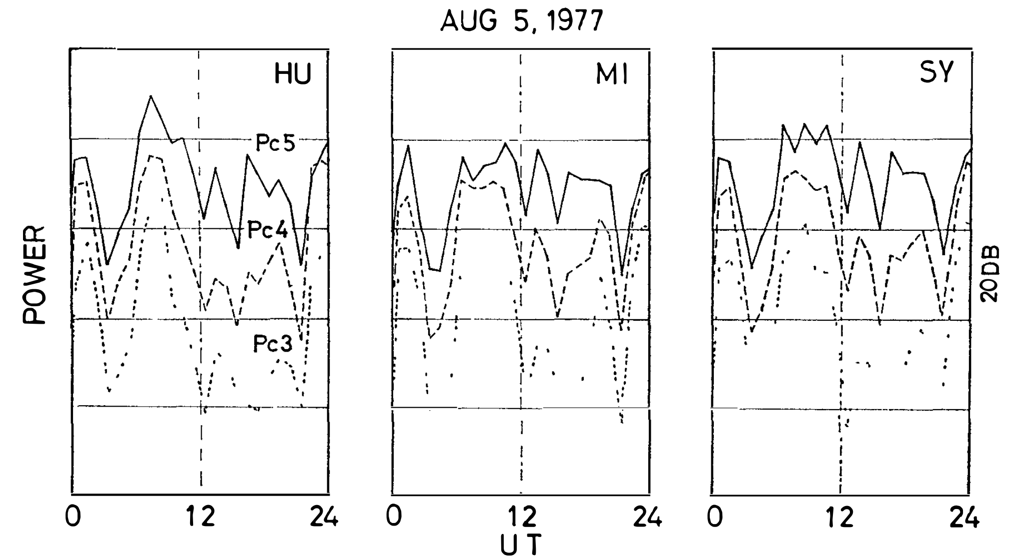

Fig 8. Hourly total powers in the Pc 3, 4 and 5 bands recorded at Husafell, Syowa and Mizuho Stations on August 5, 1977.

has a large peak in the morning hours and a small peak in the afternoon hours, while the power in the Pc 3 range has a large peak in the morning hours and the power intensity decreases greatly towards the evening. The power intensity in the Pc 4 range shows an intermediate behavior between those of the power intensities in the Pc 3 and Pc 5 ranges. A large enhancement of the power intensity near midnight is seen in all of the three frequency ranges. This enhancement comes from a contribution of burst-like pulsation activity associated with substorms

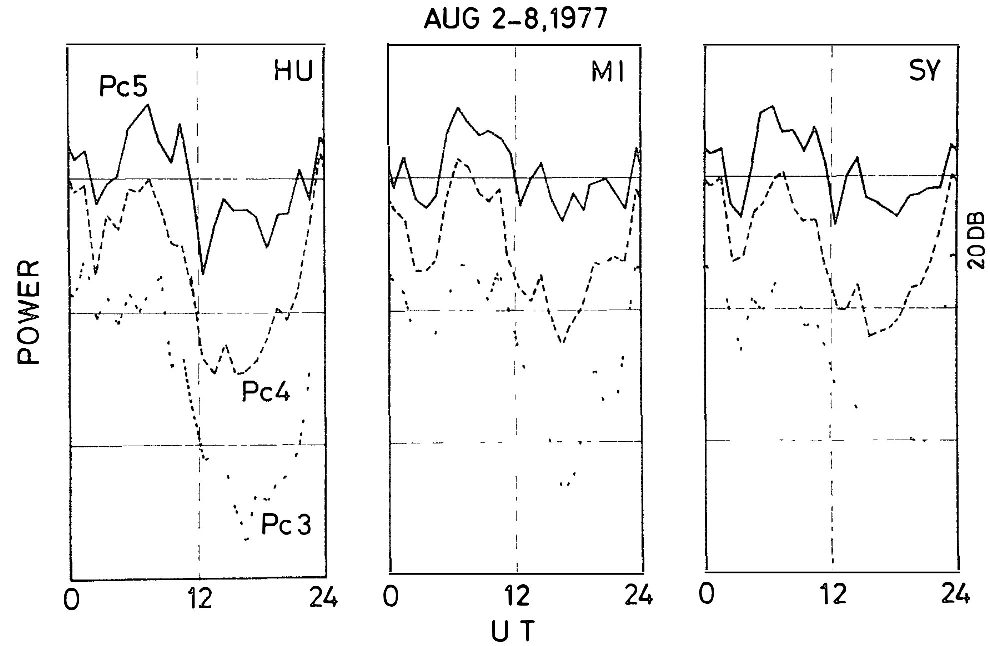

Fig 9 Hourly total powers in the Pc 3, 4 and 5 bands averaged over seven days from August 2 to 8, 1977

The diurnal variation in the power intensity similar to that given in Fig. 8 was seen almost every day during the observation period from July 29 to September 18, 1977. In order to pick up such a tendency, the hourly total powers of the *H* components in the three frequency bands were superimposed over 7 days from August 2 to 8 (Fig. 9). The result shows clearly the local time dependence of the power intensity in the Pc 3, 4 and 5 bands It is important to note that the diurnal variation of the power intensity is quite similar at the conjugate points, although the power in the Pc 5 band during the afternoon hours is higher at Syowa and Mizuho Stations in the southern hemisphere than at Husafell in the northern hemisphere

5. Diurnal Variations of the Hourly Averaged Major Axis Orientation and Ellipticity at the Conjugate Points

Plotted in Fig. 10a as a function of universal time on August 19, 1977, are the hourly averaged major axis orientations in the *H–D* plane. These values are also averaged in the three selected frequency bands. It is found that the orientation angles, with respect to the *H* direction, of the major axis of the polarization ellipses in the *H–D* plane switch from the northeast ($+\theta$) direction to the northwest direction ($-\theta$) at Mizuho Station across the magnetic local noon. Just the opposite tendency is observed at Husafell in the northern hemisphere, although a switch of the major axis orientation near local noon is not obvious in the Pc 5 band. This conjugate relation results from a phase relation that the *H* component oscillates almost in-phase at the conjugate points, while the *D* component oscillates almost out-of-phase. The result suggests that the Pc 3, 4 and 5 waves in the daytime are characterized by odd-mode standing oscillations of local resonant field lines. A switch of the major axis orientation across the local noon is not seen at Syowa Station, and the *H–D* plane ellipses are oriented preferentially in the northwest direction throughout the day. The

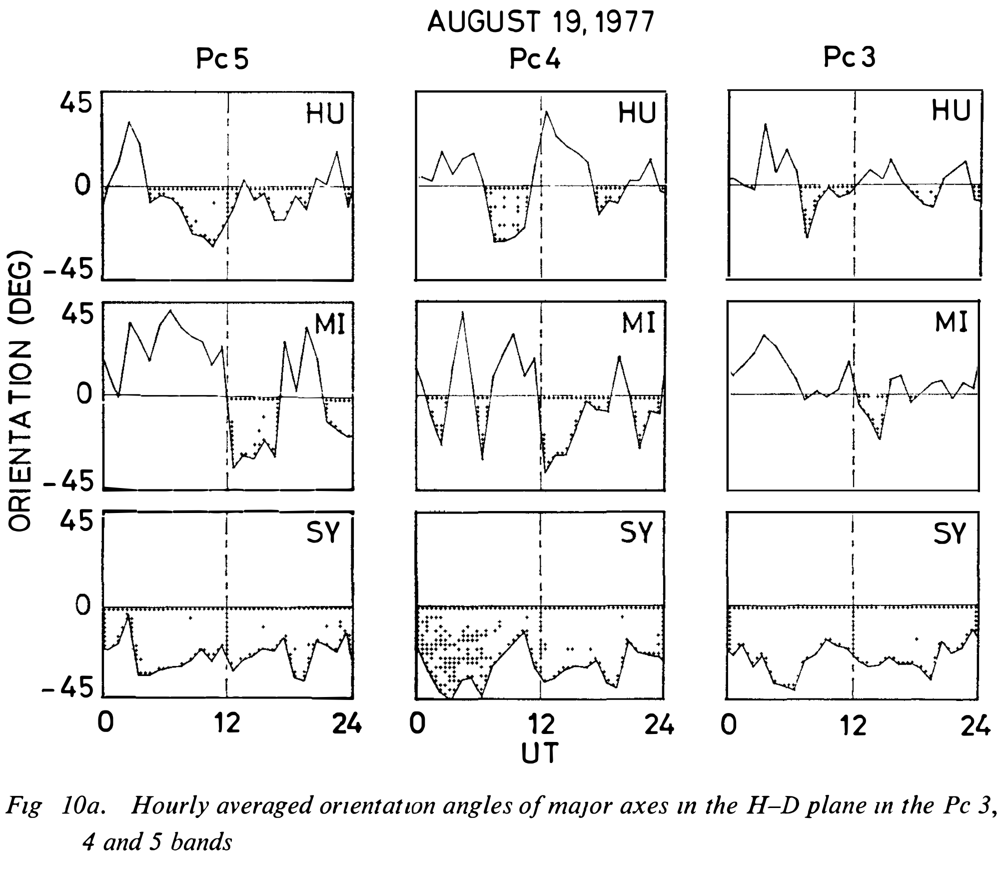

Fig 10a. Hourly averaged orientation angles of major axes in the H–D plane in the Pc 3, 4 and 5 bands

mean direction of the major axis is $\sim -25°$ in the geomagnetic coordinate which is equal to $\sim 70°$ westward from the geographic north. This fact may be interpreted by a coast-line effect (PARKINSON, 1962), since Syowa Station is located on a small island at a distance of ~ 5 km from the coast line of the Antarctic Continent, and the mean direction of the major axis in the H–D plane is almost perpendicular to the coast line.

During the nighttime, a systematic behavior is not seen in the orientation angles of the major axis at Mizuho Station and Husafell. The major axis directions are also different among the Pc 3, 4 and 5 bands. This result may indicate that magnetic pulsations at the night side are excited by several different sources.

Plotted in Fig. 10b are the hourly averaged ellipticities in the H–D plane in the Pc 3, 4 and 5 bands. The H–D plane wave ellipticity ε is defined as

$$\varepsilon = \tan \beta$$

where

$$\sin 2\beta = \frac{2\, ImPyx}{Pxx + Pyy}$$

and positive β represents left-hand polarization in the northern hemisphere and right-hand polarization in the southern hemisphere. There is a tendency that the sense of

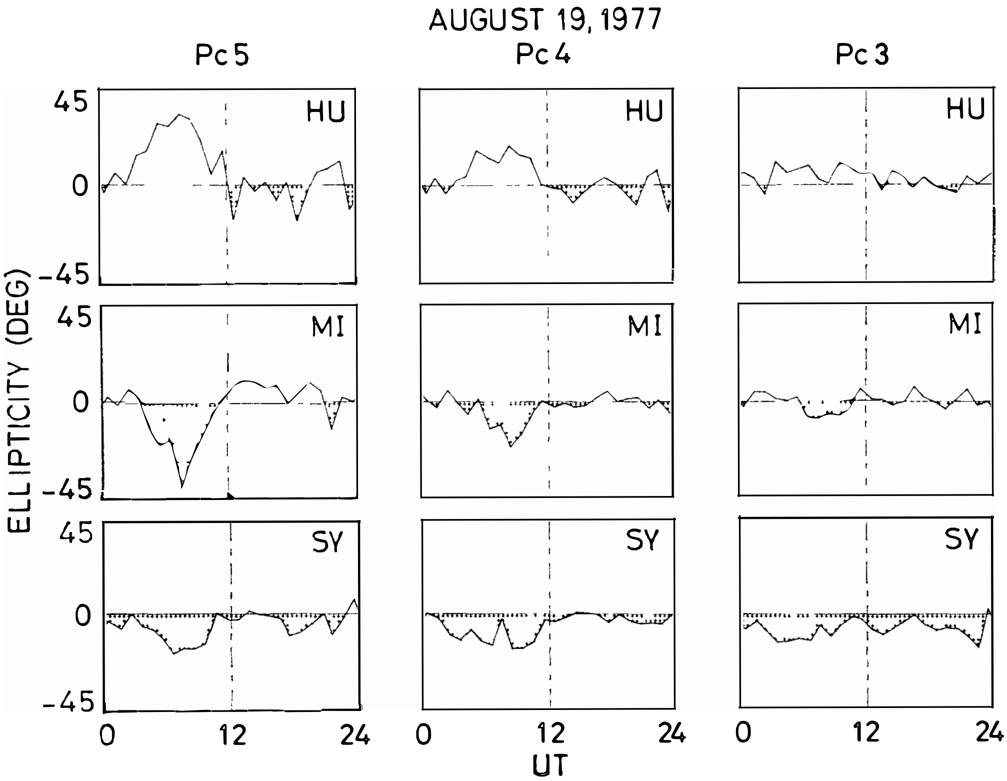

Fig 10b Hourly averaged ellipticities in the H–D plane in the Pc 3, 4 and 5 bands

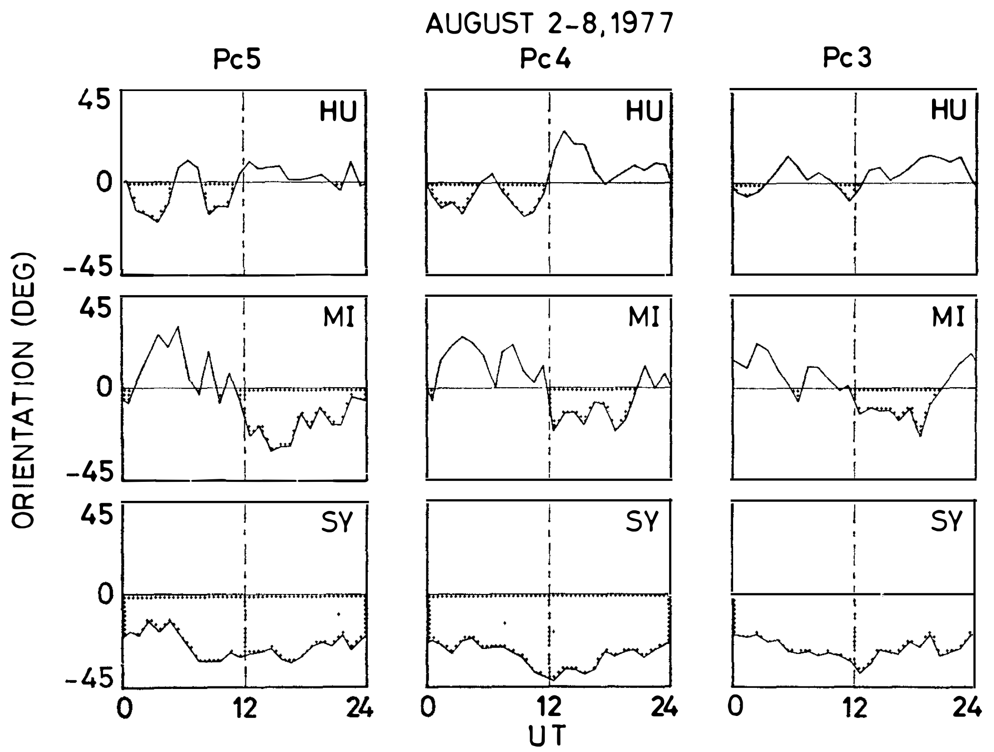

Fig. 11a. Major axis orientations in the H–D plane averaged over seven days from August 2 to 8, 1977.

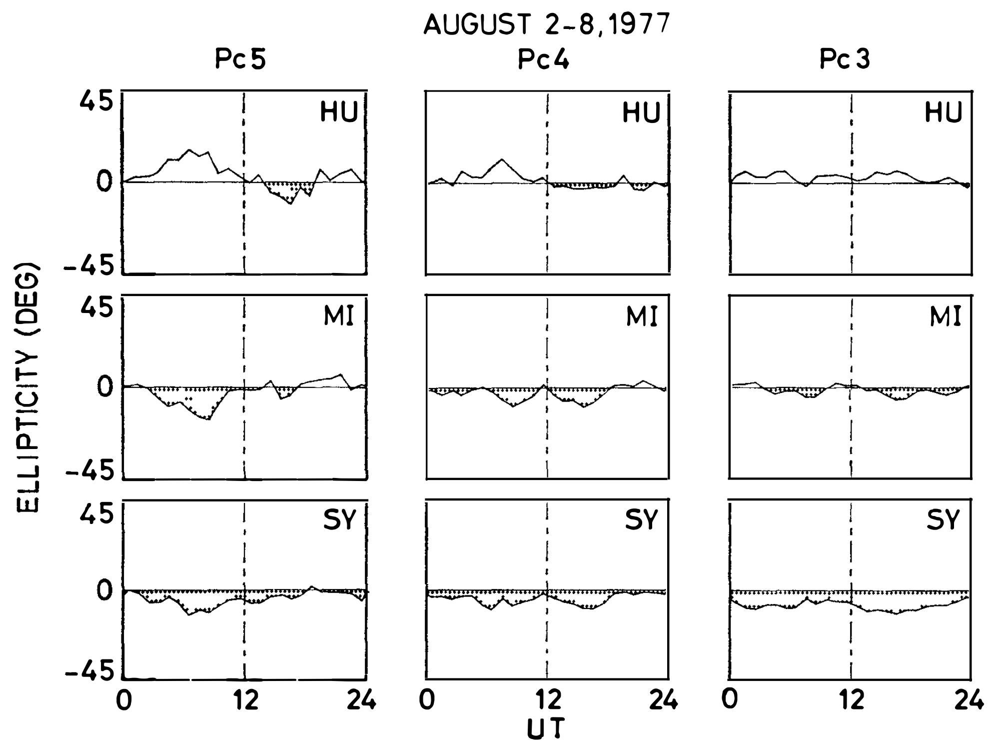

Fig 11b. Ellipticities in the H–D plane averaged over seven days from August 2 to 8, 1977.

polarization reverses in the Pc 4 and 5 bands from left-hand to right-hand across the magnetic local noon, while such a tendency is not obvious in the Pc 3 range.

The local time dependences of the major axis directions and the ellipticities presented in Figs. 10a, b is a common feature of magnetic pulsations observed at Syowa, Mizuho Stations and Husafell. Such a common feature is shown apparently by superimposing diurnal variation curves. Plotted in Figs. 11a, b as a function of universal time are the major axis orientations and the ellipticities in the *H–D* plane averaged over 7 days from August 2 to 8, 1977. The switch of the major axis orientation across the magnetic local noon is seen again at Mizuho Station and Husafell. The ellipticities show the same local time dependence as that in Fig. 10b.

6. Discussion

The characteristics of daytime magnetic pulsations observed at the Syowa Station-Iceland conjugate pair for 52 days from July 29 to September 18, 1977 are summarized as follows.

1) There are at least two pulsation bands in the Pc 3–5 frequency range. One pulsation band appears in the 20–40 mHz range with a maximum frequency at 09–12 MLT, and the other band appears in the 4–8 mHz range with a maximum frequency at 09–12 MLT. These two bands occur often independently.

2) The power intensities of these bands show significant diurnal variations. The Pc 4–5 band has a large peak in the morning hours and a small peak in the afternoon hours, while the Pc 3 band has a large peak in the morning hours and its intensity decreases sharply toward the evening.

3) The *f–t* spectral patterns are quite similar at the conjugate points, often in their fine structures, with similar diurnal variation behaviors in the power intensities.

4) In general, the conjugate phase relation of pulsation bands in the Pc 3–5 range is that the *H* components oscillate almost in-phase, while the *D* components oscillate almost out-of-phase. This phase relation suggests that the pulsation bands in the daytime are characterized by odd-mode standing oscillations of local resonant field lines.

5) The orientation angles of the major axis switch from the northeast direction to the northwest direction across the magnetic local noon at Mizuho Station, while they switch from the northwest direction to the northeast direction at Husafell. Such a tendency is more apparent in the Pc 4–5 range than in the Pc 3 range.

6) The sense of polarization is preferentially left-hand in the morning hours in the Pc 3, 4 and 5 bands, while it is close to linear in the afternoon hours.

The existence of pulsation bands in the Pc 3–5 range with the high coherency and the clear phase relation at the conjugate points suggest that the greater part of the power in the Pc 3–5 range in the daytime originates from odd-mode standing oscillations of local magnetic field lines. The pulsation bands with the center frequencies in the 4–8 mHz range correspond to magnetic pulsations observed at the magnetometer chain stations, extending from 58° to 78° geomagnetic latitude, by SAMSON and ROSTOKER (1972). They found that the periods of magnetic pulsations occurring in the daytime (0730–1730 LT) are related to the L values, at which the maximum amplitudes are observed, by the equation

$$T = -58 + (37.4 \pm 3.7)L \qquad (1)$$

This equation gives the period range of 144–188 sec and the corresponding frequency range of 5.3–6.9 mHz for magnetic pulsations with their intensity peaks at $L=6$. The equation (1) has been interpreted as the L dependence of the periods of fundamental (odd-mode) standing oscillations in the detached plasma regions (ORR, 1979). Therefore, it is likely that the pulsation bands with the frequencies in the 4–8 mHz range are fundamental odd-mode standing oscillations of magnetic field lines in the detached plasma regions near $L=6$.

The Pc 3 pulsation bands observed at Husafell, Syowa and Mizuho Stations had center-frequencies in the 20–40 mHz range. These frequencies are much higher than the frequencies of fundamental mode oscillations near $L=6$ even if the plasmatrough region is considered as their oscillation region (ORR, 1979). Therefore, the Pc 3 waves observed near $L=6$ are probably higher harmonics of odd mode oscillations of local resonant field lines. The clear switches of the orientation angles of the major axes in the *H–D* plane across the magnetic local noon indicate strongly that these waves are excited by external driving forces. At least, two different driving forces are needed, since the Pc 3 waves and the Pc 4–5 waves often occurred independently. At present two possible sources are considered as the external driving forces for Pc 3–5 waves, *i.e.*, Kelvin-Helmholtz instability on the magnetopause (SOUTHWOOD, 1974; CHEN and HASEGAWA, 1974) and waves generated by upstream protons from the bow shock (KOVNER *et al.*, 1976).

The switch of the sense of polarizations in the *H–D* plane across the magnetic local noon is not so obvious as the switch of the major axis direction. This fact is interpreted by the experimental result that the orientation of the major axis does not change across the latitude where the peak amplitude is observed, although the sense of polarization reverses on each side of the latitude with the peak intensity (LANZEROTTI *et al.*, 1974a; LAM and ROSTOKER, 1978).

The significant diurnal variations of the frequencies and the power intensities of the pulsation bands in the Pc 3–5 range strongly suggest that the excitation of MHD waves in the magnetosphere is controled not only by external driving sources but also plasma conditions in the magnetosphere. It is found that the power intensities of the pulsation bands are much higher in the morning hours than in the evening hours, particularly in the Pc 3 range. In contrast, the diurnal variations of power intensities in the Pc 3–5 range near $L=4$ are characterized by a symmetrical intensity increase around the magnetic local noon (Fukunishi, 1975b; Raspopov and Lanzerotti, 1976). Therefore, it is suggested that the coupling region of the external driving force to the local resonant field lines is located near $L=6$ in the morning hours, while it shifts toward the low latitudes in the afternoon hours, due to an increase in cold plasma density in the outer magnetosphere

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