# DAWN-DUSK ASYMMETRIES OF Pc 5 MAGNETIC PULSATIONS

Kiyohumi YUMOTO, Tohru SAKURAI* and Takao SAITO

*Onagawa Magnetic Observatory and Geophysical Institute, Tohoku University, Sendai 980*

***Abstract***: Characteristics of Pc 5 magnetic pulsations are analyzed with data of OGO-5 and ISEE-1. Ground characteristics of Pc 5 are also reviewed to discuss the correlations with those in space. The occurrence of Pc 5 in space increases with an increase in the solar wind velocity, that is consistent with the result of the ground observations. The most common Pc 5 pulsations observed at OGO-5 tend to take place while the IMF is in the Parker spiral direction. The toroidal modes ($\delta B_D \gg \delta B_H$) of Pc 5 pulsations are observed at a higher magnetic latitude and in a localized region of the dawn-side magnetosphere. The compressional and poloidal modes ($\delta B_\parallel \sim \delta B_H > \delta B_D$) of Pc 5 pulsations which penetrate from outside into the inner magnetosphere are mostly observed near the magnetic equator in the dusk-side magnetosphere. This local time asymmetry in the occurrence of dominant modes of Pc 5's in space can be explained by the velocity shear instability in the magnetospheric boundary layer with respect to characteristics of Alfvénic waves in the IMF region and the relation between the IMF direction and the Pc 5 occurrence in the magnetosphere. The asymmetrical behavior of Pc 5 pulsation activity on the ground across the noon meridian can be explained by the screening effect in the atmosphere and the ionosphere, because of the suppression of the compressional modes with a large horizontal wave number in the dusk-side magnetosphere throughout the atmosphere and the ionosphere.

## 1. Introduction

The study of the characteristics of Pc 5 magnetic pulsations has been advanced substantially in the last decade. This is due to the new techniques of measurement such as the availability of extensive magnetometer chains (SAMSON *et al.*, 1971; SAMSON and ROSTOKER, 1972), multi-satellite observations (HUGHES *et al.*, 1977, 1978; HUGHES, 1980) and auroral raders (UNWIN and KNOX, 1971; McDIARMID and McNAMARA, 1973; WALKER *et al.*, 1978, 1979). These coordinated works led to strong theoretical advances (INOUE, 1973; SOUTHWOOD, 1974; CHEN and HASEGAWA, 1974; HUGHES, 1974; HUGHES and SOUTHWOOD, 1976a, b; TAMAO, 1978; SOUTHWOOD and HUGHES, 1978). Long-period magnetic pulsations in the daytime are generally considered to be a local field line oscillation based on the idea of a steady state resonance coupling between a monochromatic surface wave excited at the magnetopause due to Kelvin-Helmholtz instability (and/or other mechanism) and a shear Alfvén wave in the magnetosphere. However, new questions are also pointed out by several workers

* Present address: Laboratory of Space Science, Tokai University, 28–4, Tomigaya 2-chome, Shibuya-ku, Tokyo 153.

(GUPTA, 1976; YUMOTO and SAKURAI, 1977; LAM and ROSTOKER, 1978). There are strong local time asymmetries in the level of Pc 5 activity on the ground and in the variance direction of Pc 5 magnetic pulsations in the magnetosphere (see Figs. 5, 7 and 13). There is no *a priori* reason for a instability to be asymmetrically excited on the magnetopause, thus, further research is required to explain the asymmetric behaviors of Pc 5 pulsations across local noon in the magnetosphere.

The aim of the present paper is to clarify the asymmetric behavior of Pc 5 magnetic pulsations in the magnetosphere and to attempt an interpretation of that with respect to both the review of the results from the ground observations and the analysis of Pc 5 pulsation from *in situ* observations. First we will indicate the relations between Pc 5 occurrence and the solar wind parameters. Occurrence characteristics of Pc 5 pulsations in the magnetosphere will be presented in Section 3, where the effect of the ionosphere and the atmosphere on the propagation of the magnetospheric signal to the ground will be also discussed. Wave characteristics of Pc 5 magnetic pulsations in space will be analyzed by examining the correlation between ground and satellite data. The observational results of Pc 5 pulsations will be summarized and theoretically discussed in the final section.

## 2. Relation of Solar Wind Parameters to Pc 5 Occurrence

Much attention has recently been given to the relationship between hydromagnetic

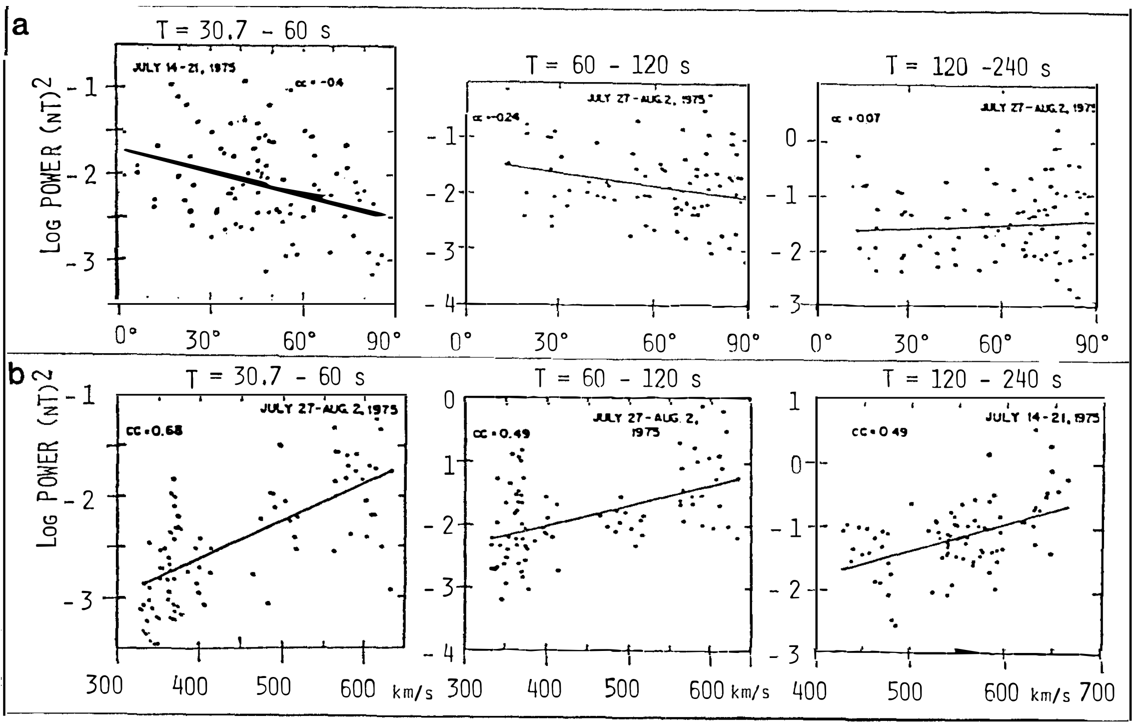



*Fig. 1.* (*a*) *Scatter plots of ground magnetic field energy (hourly averages) and the cone angle* $\theta_{XB}$ *(hourly averages) of the IMF for three period bands.*
(*b*) *Scatter plots of ground magnetic field energy (hourly averages) and the solar wind velocity* $V_{SW}$ *(hourly averages) for three period bands (after* WOLFE *et al., 1980).*

*Table 1. Details of selected Pc 5 pulsations observed by OGO-5. Pc 5 in magnetosphere (OGO-5, 1968–1969).*

| Event | UT | LT | $L$ | $\Phi$ | $Kp$ | $AE$ |
|---|---|---|---|---|---|---|
| (1968) | | | | | | |
| May 8 | 0820–0940 | 0650 | 11.0 | 14.5° | 2− | 168 |
| | 0950–1100 | 0710 | 8.9 | 13.5 | | |
| May 18 | 1950–2020 | 0620 | 8.1 | −7.0 | 3+ | 416 |
| May 21 | 1050–1140 | 0630 | 7.6 | 11.0 | 2+ | 282 |
| May 31 | 1920–1950 | 0520 | 9.0 | −7.0 | 3− | 173 |
| | 1950–2030 | 0530 | 8.3 | −9.0 | | |
| Oct. 19 | 0200–0300 | (1950) | 14.3 | (7.3) | 1− | 107 |
| | 0300–0400 | (2000) | 12.4 | (5.1) | | |
| Oct. 21 | 1230–1305 | (1925) | (17.8) | (2.5) | 1− | 37 |
| | 1350–1420 | (1930) | (16.7) | (2.3) | | |
| | 1445–1530 | (1935) | (15.9) | (2.0) | | |
| | 1640–1715 | (1940) | (14.4) | (1.7) | | |
| | 1715–1800 | (1945) | (13.6) | (1.4) | | |
| | 1820–1950 | (1955) | (12.4) | (1.1) | | |
| Oct. 27 | 0030–0230 | 1945 | 9.5 | 5.0 | 3− | 133 |
| Nov. 1 | 0510–0530 | (1930) | (11.4) | (−2.5) | 3− | 107 |
| | 0530–0610 | (1940) | (11.2) | −4.5 | | |
| Nov. 11 | 1410–1510 | (1840) | (12.1) | (−10.0) | 3− | 275 |
| | 1410–1510 | (1840) | (12.1) | (−10.0) | | |
| Nov. 29 | 2150–2220 | 1805 | 8.0 | −0.1 | $0_0$ | 20 |
| | 2220–2250 | 1815 | 7.4 | −2.0 | | |
| (1969) | | | | | | |
| Jan. 16 | 0020–0100 | 0835 | 8.5 | 30.3 | $2_0$ | 118 |
| | 0100–0140 | 0900 | 9.5 | 29.2 | | |
| | 0120–0210 | (0920) | (10.2) | 28.1 | | |
| Feb. 18 | 1310–1340 | 1220 | 8.5 | −11.0 | 0+ | 37 |
| | 1350–1420 | 1240 | 7.8 | −13.0 | | |
| Feb. 26 | 0930–1020 | 1225 | 8.1 | −28.0 | 3− | 245 |
| Mar. 3 | 2310–0000 | (0650) | (13.1) | 26.3 | 0+ | 46 |
| Mar. 4 | 0010–0050 | (0715) | (14.4) | (24.0) | $0_0$ | 45 |
| | 0104–0150 | (0730) | (16.0) | (21.0) | | |
| Apr. 1 | 0530–0630 | 1100 | 8.6 | 40.0 | 2+ | 289 |
| Apr. 14 | 0400–0600 | 0930 | 8.3 | 32.0 | 2+ | 103 |
| Apr. 27 | 0404–0440 | (0810) | (10.3) | −27.8 | 3− | 290 |
| | 0450–0530 | 0840 | 9.2 | −30.9 | | |
| May 23 | 0125–0205 | (0550) | (13.6) | −17.6 | $2_0$ | 138 |
| | 0205–0245 | (0557) | (12.5) | −17.9 | | |
| | 0245–0325 | (0610) | (11.3) | −20.0 | | |
| | 0400–0430 | 0635 | 9.6 | −22.5 | | |
| | 0445–0515 | 0650 | 8.8 | −24.0 | | |
| | 0525–0600 | 0730 | 8.0 | −27.0 | | |
| May 25 | 1635–1715 | (0520) | (12.2) | (−13.8) | 1+ | 121 |
| | 1715–1740 | (0530) | (13.1) | (−16.5) | | |
| Nov. 2 | 1735–1805 | (1850) | (16.0) | (5.0) | 3− | 772 |

*Table 1 (continued).*

| Event | $\varepsilon=\frac{a}{a-b}$ | $\theta$ | $\frac{P_{\perp}}{P_{\perp}+P_{\parallel}}$ | $\frac{P_H}{P_{\perp}}$ | Variance power (nT$^2$) | Period $T$ (s) | Polarization |
|---|---|---|---|---|---|---|---|
| (1968) | | | | | | | |
| May 8 | 0.65 | −11.4° | 0.84 | 0.14 | $3.2\times10^1$ | 375 | L |
| | 0.62 | −12.4 | 0.84 | 0.16 | 1.9 $10^1$ | 270 | conf. |
| May 18 | 0.20 | 28.6 | 0.60 | 0.44 | 1.9 $10^1$ | 270 | conf. |
| May 21 | 0.79 | −18.0 | 0.94 | 0.13 | 1.6 $10^2$ | 270, 230 | R |
| May 31 | 0.62 | 14.9 | 0.55 | 0.17 | 1.0 $10^1$ | 170 | conf. |
| | 0.65 | −20.1 | 0.79 | 0.20 | 1.9 $10^1$ | 210 | conf. |
| Oct. 19 | 0.51 | 43.7 | 0.32 | 0.49 | 2.2 $10^1$ | 540 | L |
| | 0.49 | 9.7 | 0.35 | 0.23 | 1.6 $10^1$ | 400 | R |
| Oct. 21 | 0.30 | 87.4 | 0.08 | 0.67 | 5.0 $10^1$ | 420 | R |
| | 0.51 | −55.7 | 0.13 | 0.61 | 7.0 $10^1$ | 400 | R |
| | 0.68 | −71.2 | 0.44 | 0.83 | 2.5 $10^1$ | 400 | R |
| | 0.23 | −74.4 | 0.35 | 0.61 | 2.3 $10^1$ | 360 | R |
| | 0.42 | −59.5 | 0.54 | 0.62 | 0.9 $10^1$ | 450 | R |
| | 0.44 | −73.3 | 0.65 | 0.72 | 1.1 $10^1$ | 360 | R |
| Oct. 27 | 0.39 | 5.2 | 0.52 | 0.28 | 3.2 $10^1$ | 600 | R |
| Nov. 1 | 0.47 | −50.2 | 0.19 | 0.55 | 9.3 $10^1$ | 300 | L |
| | 0.57 | −61.4 | 0.24 | 0.69 | 2.9 $10^1$ | 375 | L |
| Nov. 11 | 0.58 | −69.2 | 0.40 | 0.76 | 3.2 $10^1$ | 500 | conf. |
| | | | | | 0.8 $10^1$ | 210 | L |
| Nov. 29 | 0.41 | 20.6 | 0.92 | 0.32 | 0.4 $10^1$ | 300 | R and L |
| | 0.38 | 4.7 | 0.96 | 0.28 | 1.3 $10^1$ | 400 | L |
| (1969) | | | | | | | |
| Jan. 16 | 0.26 | −4.2 | 0.93 | 0.35 | 7.2 $10^1$ | 320 | L |
| | 0.23 | 16.1 | 0.92 | 0.39 | 0.6 $10^1$ | 440 | L |
| | 0.51 | 16.4 | 0.92 | 0.24 | 4.3 $10^1$ | 530 | L |
| Feb. 18 | 0.65 | 47.5 | 0.98 | 0.53 | 0.4 $10^1$ | 260 | conf. |
| | 0.40 | 27.9 | 0.94 | 0.37 | 1.6 $10^1$ | 210 | conf. |
| Feb. 26 | 0.67 | −19.9 | 0.97 | 0.19 | 2.6 $10^2$ | 430 | R |
| Mar. 3 | 0.63 | 22.8 | 0.86 | 0.23 | 1.7 $10^1$ | 450 | L and R |
| Mar. 4 | 0.45 | −2.1 | 0.84 | 0.23 | 1.3 $10^1$ | 420 | L |
| | 0.75 | 38.9 | 0.64 | 0.41 | 1.7 $10^1$ | 450 | L |
| Apr. 1 | — | — | — | — | — — | — | — |
| Apr. 14 | — | — | — | — | — — | — | — |
| Apr. 27 | 0.66 | 18.5 | 0.73 | 0.18 | 5.2 $10^1$ | 310 | L |
| | 0.70 | 17.3 | 0.88 | 0.16 | 8.1 $10^1$ | 310 | L |
| May 23 | 0.84 | 32.2 | 0.89 | 0.29 | 1.0 $10^2$ | 420 | L |
| | 0.56 | 33.0 | 0.70 | 0.36 | 6.0 $10^1$ | 420 | L |
| | 0.63 | 10.6 | 0.78 | 0.15 | 1.1 $10^2$ | 420 | L |
| | 0.87 | 25.5 | 0.92 | 0.20 | 5.8 $10^2$ | 330 | L |
| | 0.82 | 24.4 | 0.93 | 0.19 | 1.3 $10^2$ | 300 | L |
| | 0.85 | 14.5 | 0.96 | 0.08 | 1.4 $10^2$ | 280 | L |
| May 25 | 0.54 | 82.1 | 0.74 | 0.81 | 5.9 $10^1$ | 370 | conf. |
| | 0.64 | 38.5 | 0.76 | 0.41 | 1.7 $10^2$ | 370 | conf. |
| Nov. 2 | 0.63 | −85.0 | 0.11 | 0.88 | 1.2 $10^2$ | 360 | L |

energies measured on the surface of the earth and interplanetary parameters (GUL'ELMI, 1974; WEBB and ORR, 1976; SINGER *et al.*, 1977; WEBB *et al.*, 1977). GREENSTADT *et al.* (1980), reviewing the evidence, indicated that for control by the solar wind, the two important and independent parameters are $V_{SW}$, the solar wind velocity and $\theta_{XB}(=\cos^{-1} |B_X|/B)$ the cone angle of IMF, where $B_X$ is a component of IMF in the direction of Sun–Earth line and $B$ expresses the total value. WOLFE *et al.* (1980) demonstrated that the solar wind velocity effect is important for producing dayside ground-based magnetic field energy in the Pc 3–5 range. A higher solar wind velocity produces the magnetic variation energy. The instability driven by the solar wind flow at the magnetopause is more likely to occur at higher solar wind velocities, thereby leading to hydromagnetic wave generation that is subsequently detected at the earth's surface (SOUTHWOOD, 1968; YUMOTO and SAITO, 1980). WOLFE *et al.* (1980) also showed that the dependence of hydromagnetic wave energy on $\theta_{XB}$ was fairly apparent in the Pc 3–4 range, whereas $V_{SW}$ was correlated mostly with the Pc 5 range activity, where the $\theta_{XB}$ effect was not apparent as shown in Fig. 1.

We present here the relations between the occurrence of Pc 5 pulsations observed in space and the solar wind parameters. Hourly averages of the solar wind velocity and the direction of the IMF, while Pc 5 pulsations were measured by OGO-5, refer to the interplanetary medium data book (KING, 1977). Table 1 gives characteristics of selected Pc 5 pulsations observed by OGO-5. The dependence of Pc 5 occurrence on the solar wind velocity is shown in the right panel of Fig. 2. The occurrence of Pc 5 pulsation in the magnetosphere increases with an increase in the solar wind velocity. The relation with velocity suggests that Pc 5 occurrence should be connected in some way with the stream structure of the solar wind. The key parameter for the Kelvin-Helmholtz model is the solar wind speed. A surface separating two fluids can be excited to produce growing waves if one fluid flows along the surface with sufficient velocity relative to the other. The instability grows when the relative velocity is above a threshold speed. This result is in agreement with that of the ground-based observation, there-

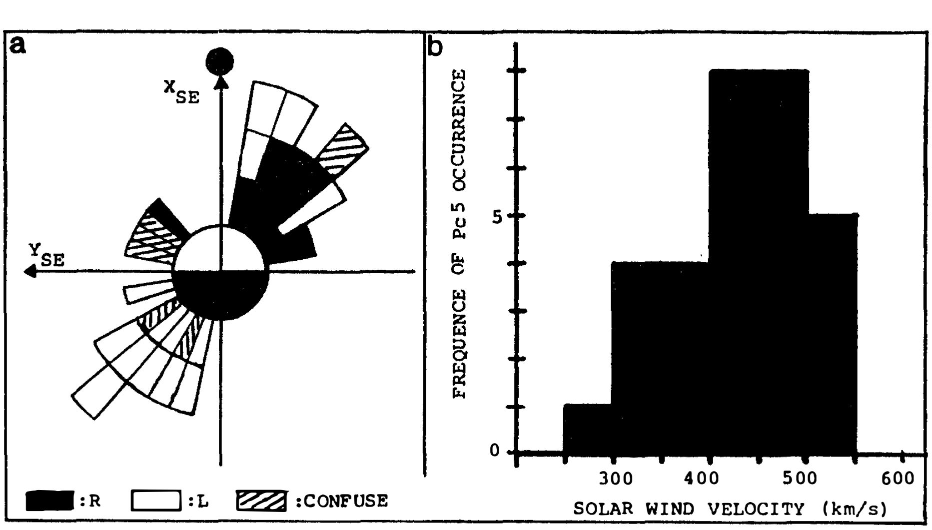



*Fig. 2. Relation between Pc 5 occurrence in space and solar wind parameters.*
*(a) IMF direction (hourly averages) while the Pc 5 pulsations were observed by OGO-5.*
*(b) Solar wind velocity (hourly averages) and the frequency of Pc 5 occurrence in space.*

fore, Pc 5 magnetic pulsation is more likely generated by the instability driven by the solar wind flow at the magnetopause. In addition to this "velocity effect", it is found that the most common Pc 5 pulsations in space are correlative with the IMF direction coincident with that of the Parker spiral as shown in the left panel of Fig. 2. The relation between the occurrence characteristic of the Pc 5 polarization and the IMF direction will be theoretically discussed later.

## 3. Occurrence Characteristics of Pc 5 Magnetic Pulsations

In the last decade, *in situ* observations have revealed the existence of various modes of Pc magnetic pulsations in the magnetosphere (BARFIELD *et al.*, 1972; BOSSEN *et al.*, 1976a, b; YUMOTO and SAKURAI, 1977; KOKUBUN *et al.*, 1977; HUGHES *et al.*, 1978; KOKUBUN, 1980). Statistical studies have shown that most of Pc 3–5 pulsations can be classified into the two types, *i. e.*, transverse and compressional pulsations. ARTHUR *et al.* (1977) and ARTHUR (1978) had also classified the Pc 3–5 pulsations into the two types, azimuthally and radially polarized pulsations, according to the orientation of the wave ellipse. These azimuthal and radial Pc 5 pulsations mostly have transverse and compressional components, respectively, which will be demonstrated in Fig. 14.

The data used in this study were from the University of California, Los Angeles, triaxial fluxgate magnetometers on OGO-5, ISEE-1 and -2 satellites. Analog data of OGO-5 in the solar-magnetospheric coordinates had been provided by the National Space Science Data Center through the World Data Center-A. Analog data of ISEE-1 and -2, which were represented by four-second average data in the solar-ecliptic coordinates, are by courtesy of Prof. C. T. RUSSELL, UCLA. In order to obtain clear Pc 5 wave characteristics observationally, we had to put the following three criteria on the data sampling: (1) The data were chosen where the OGO-5, ISEE-1 and -2 satellites were in the dayside magnetosphere and in the outer flanksides ($L \gtrsim 10$) between $\sim$0400 and $\sim$2000 LT. The data in the midnight sector were excluded in the present study. (2) In order to avoid contamination by Ps 6 type Pi 3 events (SAITO, 1978; SAITO and YUMOTO, 1981) having the irregular, burstlike appearances of Pi 2 magnetic pulsations as seen on the ground were also excluded from consideration. (3) Pc 5 events whose amplitudes are larger than $\sim$3 nT were selected to avoid artificial noise caused by data processing. Being restricted by the above-mentioned three severe conditions, we could select 40 events of OGO-5 during 21 months from March 1968 to November 1969 and 20 events of ISEE-1 and -2 during 4 months from November to December 1977 and from July to August 1978 as shown in Tables 1 and 2, respectively.

Figure 3 indicates two typical examples of the transverse and compressional Pc 5 pulsations observed by ISEE-1 in the dawn-side and the dusk-side magnetosphere, respectively. The transverse modes have no fluctuations in total component of the magnetic field, and the compressional modes have large fluctuations in the total component. In general, the transverse Pc 5 on the dawn side tends to be observed in a localized region of the magnetosphere, and the compressional Pc 5 on the dusk side measured continuously from outside to inside the magnetosphere as shown in Fig. 3. The total powers ($|\delta B|^2$) of Pc 5 magnetic pulsations, which will be defined in the next section, are shown in Fig. 4 against the $L$-values where Pc 5 pulsations were observed

Table 2. *Characteristics of selected Pc 5 pulsations observed by ISEE-1 and ISEE-2.*

| Date | UT | LT | $L$ | $\Phi$ | $T$ | $P_{\perp}/P_{\mathrm{total}}$ | $\delta B_{\parallel}$ | $\delta B_X$ | $\delta B_Y$ | $\delta B_Z$ | $\bar{F}$ | $\bar{B}_X$ | $\bar{B}_Y$ | $\bar{B}_Z$ | Polarization |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | s | | nT | nT | nT | nT | nT | nT | nT | nT | |
| Nov. 22, 1977 | 2010–2035 | 06 00 | 10 | 20° | 320 | 0 99 | 0.2 | 2.0 | 1.2 | 0.4 | 56 | −6 | 48 | 33 | L |
| | 2110–2150 | 06 30 | 11.3 | 19 | 330 | 0.51 | 4.4 | 4.4 | 4.0 | 2.0 | 32 | −7 | 20 | 23 | L |
| | 2300–2325 | 07 00 | 13.6 | 18 | 230 | 0.24 | 4.6 | 2.3 | 1.2 | 4.6 | 22 | −6 | 8 | 18 | L |
| Nov. 25, 1977 | 0630–0710 | 07 20 | 14.8 | 32 | 600 | 0.84 | 2.0 | 2.5 | 1.8 | 4.0 | 31 | −8 | 27 | 13 | lin. |
| Dec. 7, 1977 | 0430–0530 | 06 15 | 12.6 | 31 | 570 | 0.98 | 0.6 | 2.0 | 1.1 | 4.0 | 48 | 2 | 48 | 7 | L |
| | 0530–0700 | 06 45 | ~16 | 33 | 640 | 0.94 | 3.0 | 7.0 | 3.0 | 9.0 | 24 | 2 | 24 | 5 | L & lin. |
| Dec. 14, 1977 | 0700–0800 | 05 00 | 12.3 | 41 | 340–550 | — | — | — | — | 7.0 | 200 | 70 | 200 | 10 | — |
| | 0800–0900 | 05 30 | 16.5 | 41 | 570 | 0.98 | 0.8 | 4.0 | 1.6 | 4.0 | 82 | 21 | 80 | 2 | lin. |
| Dec. 28, 1977 | 1600–1800 | 03 45 | 10.7 | 22 | 500 | 0.92 | 6.0 | 10.0 | 16.0 | 10.0 | 54 | 34 | 36 | 14 | L |
| July 19, 1978 | 0920–1000 | 18 10 | 13.2 | −15 | 450 | 0.04 | 8.0 | 2.5 | 3.6 | 7.0 | 15 | 1 | 6 | 13 | R |
| | 1030–1100 | 18 15 | 12.4 | −17 | 300–450 | 0.19 | 10.0 | 1.8 | 7.5 | 8.0 | 25 | 1 | 13 | 22 | L |
| | 1110–1230 | 18 20 | 11.3 | −19 | 600 | 0.04 | 12.0 | 2.5 | 8.5 | 8.5 | 34 | 1 | 22 | 27 | L |
| July 24, 1978 | 0100–0300 | 17 45 | $\gtrsim$15 | 19 | 900 | 0.18 | 25.0 | 6.0 | 25.0 | 10.0 | 25 | 7 | −16 | 16 | R |
| | 0300–0430 | 18 00 | 14.5 | 5 | 820 | 0.54 | 16.0 | 5.0 | 21.0 | 10.0 | 25 | 6 | −10 | 16 | R |
| | 0430–0600 | 18 20 | 11.3 | −10 | 600 | 0.35 | 10.0 | 2.0 | 10.0 | 7.0 | 27 | 4 | 2 | 26 | R |
| | 0600–0730 | 18 40 | 9.0 | −19 | 450 | 0.04 | 14.0 | 2.5 | 6.5 | 12.5 | 35 | 0 | 15 | 30 | L |
| July 26, 1978 | 1200–1230 | 17 20 | 16.2 | −11 | 450 | 0.06 | 4.0 | 2.0 | 2.0 | 3.0 | 15 | 7 | −4 | 13 | lin. |
| | 1235–1410 | 17 30 | 13.7 | −11 | 360–450 | 0.26 | 8.0 | 3.5 | 5.0 | 7.0 | 15 | 7 | −2 | 13 | R |
| Aug. 5, 1978 | 0300–0500 | 17 35 | 11.5 | −6 | 250–450 | 0.81 | 15.0 | 7.0 | 30.0 | 15.0 | 24 | 2 | 0 | 23 | R |
| | 0500–0540 | 17 45 | 10.5 | −11 | 410 | 0.06 | 12.0 | 5.0 | 8.0 | 8.0 | 34 | 0 | 18 | 28 | L |

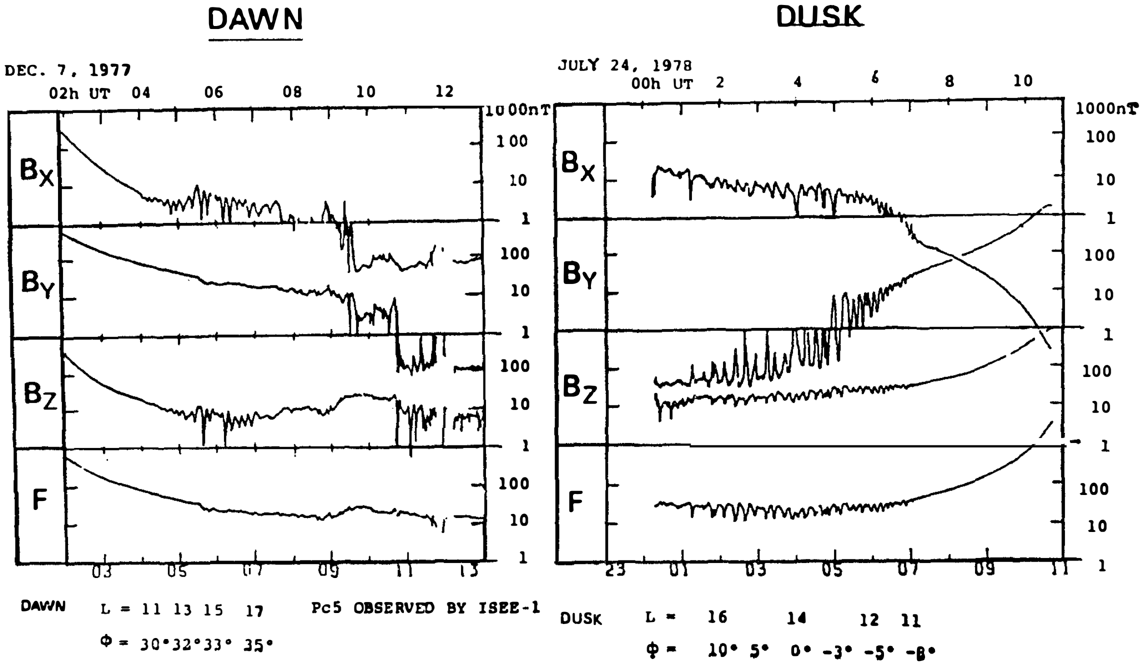



*Fig. 3. Typical examples of a transverse Pc 5 in the dawn-side magnetosphere and a compressional Pc 5 in the dusk-side magnetosphere, respectively. The dominant modes are distinguished with respect to the fluctuations in the total component (F).*

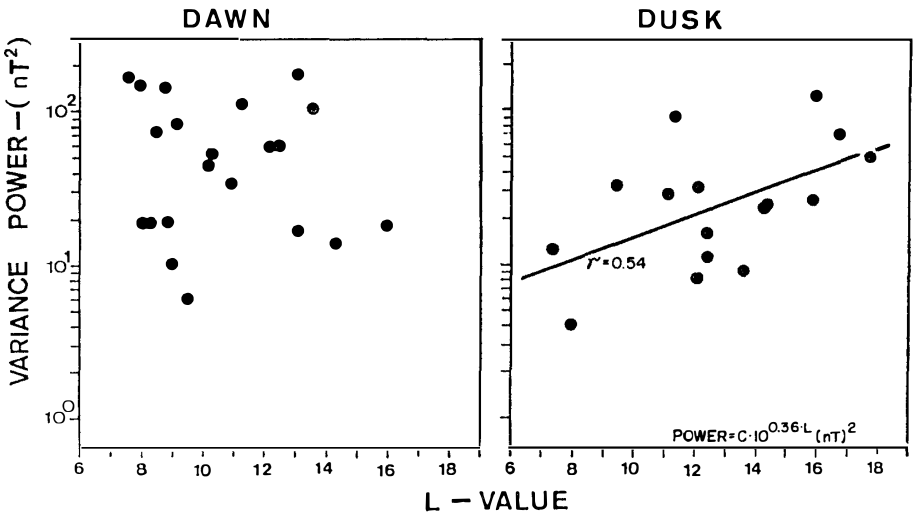



*Fig. 4. L-value dependence of the variance power of Pc 5 pulsations observed by OGO-5. Left- and right-panels indicate Pc 5's in the dawn-side and in the dusk-side magnetosphere, respectively.*

by OGO-5. The variance powers of Pc 5 on the dusk side are comparable to those on the dawn side. It is also interesting to note no relation between the total power of Pc 5 and the $L$-value in the dawn side and a positive correlation in the dusk side. These results in Figs. 3 and 4 would lead one to believe that Pc 5 pulsations in the dusk side are compressional waves which penetrate from outside to inside the magnetosphere.

The magnetic variance ratios ($P_\perp/P_\perp+P_\parallel$) of Pc 5 pulsations observed by ISEE-1

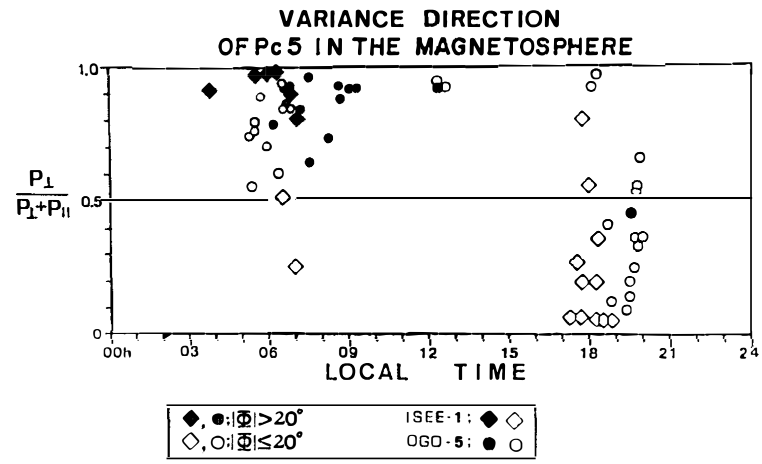



*Fig. 5. Local time dependence of the variance direction ($P_{\perp}/P_{\perp}+P_{\parallel}$) of Pc 5 pulsation in space. A diamond and a circle express Pc 5's observed by ISEE-1 and by OGO-5, respectively. Black and white ones stand for Pc 5 pulsations observed at higher magnetic latitude and near magnetic equator.*

and OGO-5 are shown in Fig. 5 against local time and magnetic latitude, where $P_{\perp}$ and $P_{\parallel}$ stand for variance powers normal $(\delta B_{\perp})^2$ and parallel $(\delta B_{\parallel})^2$ to the ambient magnetic field, respectively. The transverse modes are represented by $(P_{\perp}/P_{\perp}+P_{\parallel})\sim 1.0$, and the compressional modes by $(P_{\perp}/P_{\perp}+P_{\parallel})\sim 0.0$, where the derivation is represented in Figs. 9, 10 and 11. A diamond and a circle express Pc 5 pulsations observed by ISEE-1 and OGO-5, and black and white ones stand for Pc 5 pulsations at higher magnetic latitude ($\Phi\gtrsim 20°$) and near magnetic equator ($\Phi<20°$), respectively. It is found that the transverse modes in the Pc 5 frequency range dominate in the dawn sector, and the compressional modes are mostly observed in the dusk sector. It should also be worth mentioning that latitudinal structure of hydromagnetic waves in space must be considered in interpretation of statistical characteristics such as the local time dependence of occurrence. The transverse modes are observed at higher magnetic latitude, and the compressional modes near magnetic equator. Trajectories of OGO-5 and ISEE-1 observing Pc 5 pulsations are drawn in local time–$L$-value and magnetic latitude–radial distance projections, respectively (Fig. 6). The transverse pulsations are expressed by solid lines, and those of the compressional pulsations by dotted lines. The occurrences of the transverse and the compressional Pc 5 pulsations have a maximum around 0700 LT and $\Phi\gtrsim 20°$ and a peak around 1900 LT and $\Phi<20°$, respectively. There is no dawn-dusk asymmetry in the OGO-5 trajectory, that had been confirmed with the OGO-5 Ephemeris provided by the World Data Center-A. OGO-5 also made many trajectories at higher latitude in the dusk-side and near the magnetic equator in the dawn-side magnetosphere. Therefore, the dawn-dusk asymmetry of the Pc 5 occurrences must be due to an excitation and/or a propagation mechanism of Pc 5 pulsation in the magnetosphere.

If Pc pulsations are the fundamental mode of standing oscillations along the field line, the transverse magnetic component should not be measured on the equatorial plane (*cf.* Fig. 6). Such a feature was first noted in the survey of Pc 5 pulsations by KOKUBUN *et al.* (1976, 1977). They found that transverse Pc 5 pulsations were not detected near the magnetic equator ($\Phi\leq 10°$). SINGER and KIVELSON (1979) have

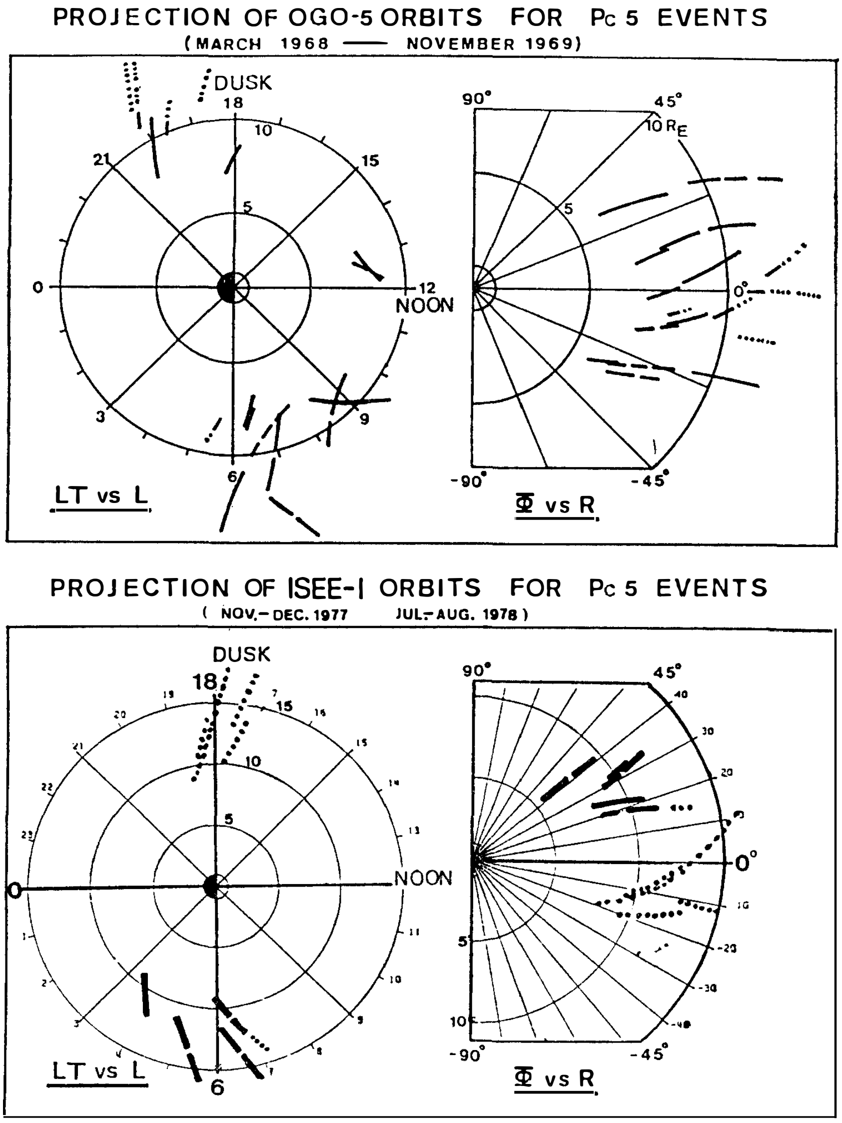



*Fig. 6. Trajectories of OGO-5 and ISEE-1, while Pc 5 pulsations were being observed, in local time-L-value and in magnetic latitude-radial distance projections. Solid and dotted lines express the transverse and the compressional Pc 5 pulsations, respectively.*

further examined the latitudinal structure of Pc 5 wave by using simultaneous magnetic field and ion flux data. HUGHES *et al.* (1978) demonstrated that the azimuthal wave-number of the transverse wave (*i.e.*, azimuthal mode) in the dawn sector is smaller than that of the compressional wave (*i. e.*, radial mode) in the dusk sector, as shown by multi-satellite observations. Theory of eigen-oscillation, which is discussed by YUMOTO and SAITO (1982), predicts that long-period pulsations with small azimuthal wavenumber correspond to the standing resonance oscillations, and long-period pulsations with large azimuthal wavenumber to an evanescent compressional wave in the magneto-sphere.

On the other hand, the use of arrays of closely spaced magnetometers on the ground in the early 1970's revealed the spatial characteristics of Pc 4–5 pulsations (SAMSON *et al.*, 1971) and would appear to provide powerful support for an instability driven by the solar wind as a source of the pulsation energy. However, there is a strong local time asymmetry in the level of Pc 4–5 activity with a preponderance of activity observed in the pre-noon sector and the activity level being clearly suppressed in the post-noon sector as shown in Fig. 7 (after KOKUBUN and NAGATA, 1965; *cf.* figure of GUPTA, 1976). There is no *a priori* reason for an instability driven by the solar wind on the magnetopause to be preferentially excited on the pre-noon flank as opposed to the post-noon flank. Some of magnetic pulsations in the post-noon magnetosphere have not yet been identified on the ground (BAIRFIELD and MCPHERRON, 1972a, b; HEDGECOCK, 1976). Thus, theoretical research is needed to explain the asymmetric behavior of pulsational activity across the noon meridian. Theoretical considerations of the screening of magnetospheric signals by the atmosphere and the ionosphere have indicated that the ground observations are limited to detecting magnetospheric signals of a horizontal scale length less than ~120 km at the ionospheric level (HUGHES and SOUTHWOOD, 1976a, b). If the Hall conducting region above a height $h$ in the ionosphere is of thickness $d$, we have approximately the ratio of the perturbation field ($\delta B_g^x$) on

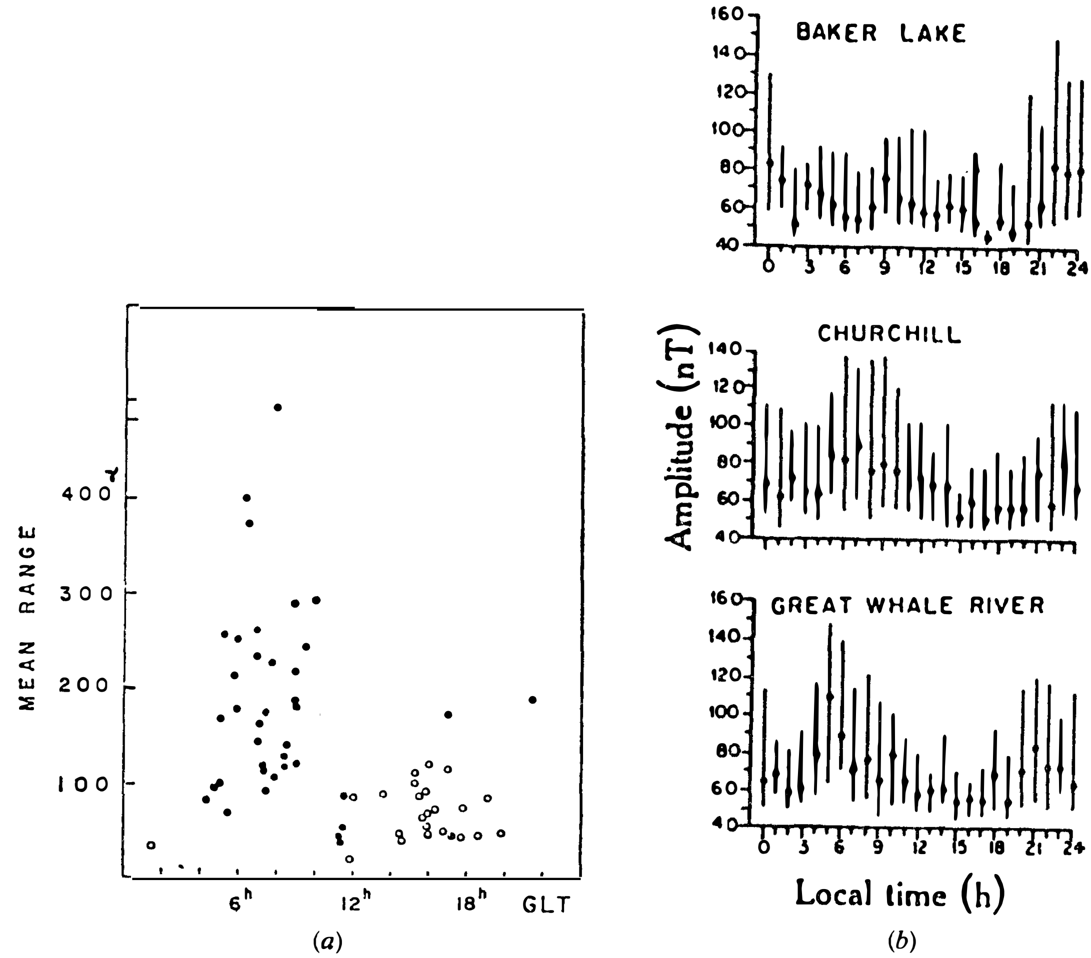



*Fig. 7. Local time asymmetry in the level of Pc 4–5 activity on the ground.*
*(a) Local time dependence of the mean horizontal range at College. Black circle; counterclockwise pulsation, open circle; clockwise pulsations (after KOKUBUN and NAGATA, 1965). (b) Amplitudes of Pc 5 pulsations at a high latitude (Baker Lake), and two auroral oval (Churchill and Great Whale River) stations (after GUPTA, 1976).*

the ground to the field ($\delta B_M^y$) with wavenumber $k$ in the magnetosphere as the following equation;

$$(\delta B_g^x/\delta B_M^y) = -e^{-kh}(\Sigma_H/\Sigma_P)[1+(kd/2)], \tag{1}$$

where $\Sigma_H$ and $\Sigma_P$ are the height-integrated Hall and Pedersen conductivities, respectively. Typically, $d \sim 20$ km and $h \sim 120$ km, the ratio of the ground magnetic field to the magnetospheric field is thus roughly $e^{-kh}\Sigma_H/\Sigma_P$ for $k > (120\text{ km})^{-1}$, and short-horizontal scale disturbances are reduced in amplitude on the ground as shown in Fig. 8. Therefore, the activity level of the compressional Pc 5 pulsations with large horizontal wavenumber in the post-noon magnetosphere as illustrated in Fig. 5 is expected to be suppressed on the ground as shown in Fig. 7. Moreover, HUGHES *et al.* (1978) demonstrated that the azimuthal wavenumber of the azimuthal mode in the dawn sector is smaller than that of the compressional mode in the dusk sector. The asymmetric behavior of pulsational activity on the ground across the noon meridian can be explained by the screening effect in the atmosphere and the ionosphere.

It is summarized that the transverse modes of the Pc 5 pulsations tend to be observed at higher magnetic latitude in the dawn-side magnetosphere, and the compressional modes which penetrate from outside to inside the magnetosphere are mostly observed near magnetic equator in the dusk-side magnetosphere. The compressional modes with large wavenumber in the post-noon magnetosphere can be suppressed on the ground. The asymmetric occurrence of dominant modes in the magnetosphere is important in understanding the driving mechanisms for Pc 5 pulsations and will be theoretically discussed in the final section.

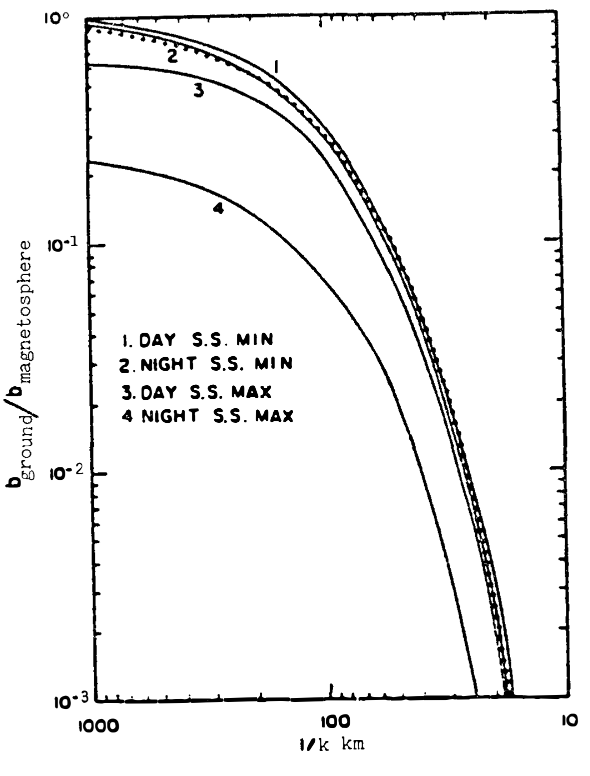



*Fig. 8. The ratio of the ground magnetic field to the magnetospheric field ($e^{-kh}\Sigma_H/\Sigma_P$). The function $e^{-kh}$ with $h$ = 120 km is shown as a line of dots (after* HUGHES *and* SOUTHWOOD, *1976b).*

## 4. Wave Characteristics of Pc 5 Magnetic Pulsations

Wave characteristics of Pc 5 pulsations observed by OGO-5 in the magnetosphere are first analyzed to know about polarization properties of Pc 5 pulsations, which are associated with the generation and propagation mechanisms in space. The three-component analog magnetograms of OGO-5 were expanded and digitized with a semi-automatic digitizer, Graf/Pen, with a sampling period of 30 s. The digitized magnetograms in the SM coordinate system were then transferred into a magnetic field line coordinate system as illustrated in Fig. 9. In the magnetic field line coordinates ($B_0$, $D$, $H$), the $B_0$-axis is taken parallel to the local geomagnetic field, the $D$-axis azimuthally westward perpendicular to the $B_0$-axis and the $Z_{SM}$-axis, and the third $H$-axis, defined by $e_H = e_D \times e_{B_0}$, nearly radial outward from the center of the earth through the satellite near the magnetic equator. The transferred data in the ($B_0$, $D$, $H$)-coordinates

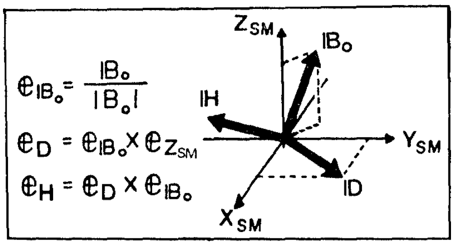



*Fig. 9. A magnetic field coordinates system ($B_0$, $D$, $H$). $B_0$-axis is parallel to the ambient magnetic field, D-axis azimuthally westward normal to the $B_0$-$Z_{SM}$ plane, and H-axis defined by $e_H = e_D \times e_{B_0}$, i. e., radial outward from the center of the earth through the satellite position near the magnetic equator.*

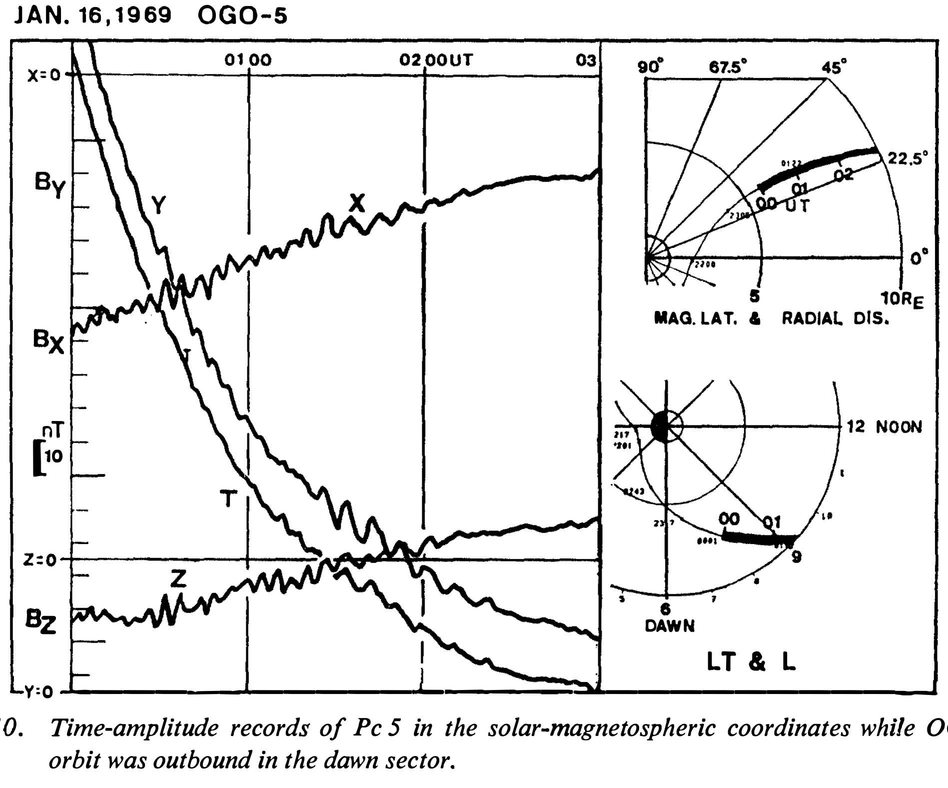



*Fig. 10. Time-amplitude records of Pc 5 in the solar-magnetospheric coordinates while OGO-5 orbit was outbound in the dawn sector.*

system were subjected to power spectral and polarization analyses.

Figure 10 indicates an example of time-amplitude records of the selected Pc 5 event in the SM coordinates obtained at OGO-5, whose orbit is shown to be outbound in the dawn sector for the two hours from 0030 to 0230 UT on January 16, 1969. It is clearly recognized to be difficult to identify the dominant mode of the Pc 5 magnetic variations in the SM coordinates, which can easily be examined by comparing the variance powers in the ($B_0$, $D$, $H$)-coordinates. After the digitized magnetograms in the SM coordinates are transferred into the ($B_0$, $D$, $H$)-coordinates, the trends of the transferred data are removed in the input time series by the least mean squares fitting of a second order polynomial as shown in Fig. 11a. Amplitudes of the Pc 5 event are larger in $D$ and $H$ than in $B_0$. The variance direction of the Pc 5 event is nearly confined to the plane normal to the local magnetic field. Magnetic pulsation of this type can be categorized as a transverse mode. The polarization analysis was given by drawing disturbance hodographs in the $H$-$D$ plane. The hodograph of the Pc 5 event indicates the left-handed polarization. Power spectra of the Pc 5 pulsations observed by OGO-5 were also obtained to examine the power ratios of ($P_\perp/P_\perp+P_\parallel$) and ($P_H/P_\perp$), and the dominant period as illustrated in Fig. 11b, where $P_\perp=P_H+P_D$ and $P_\parallel$, $P_D$ and $P_H$ are power spectra in the $B_0$-, $D$- and $H$-directions, respectively. The total power of Pc 5 magnetic variations is defined as $P_{total}=P_\perp+P_\parallel$, *i.e.*, $(\delta B_{total})^2=(\delta B_\perp)^2+(\delta B_\parallel)^2$. Figure 12 shows two typical examples of time-amplitude Pc 5 pulsations in the magnetic field coordinates on the dawn-side and the dusk-side magnetosphere, respectively. The

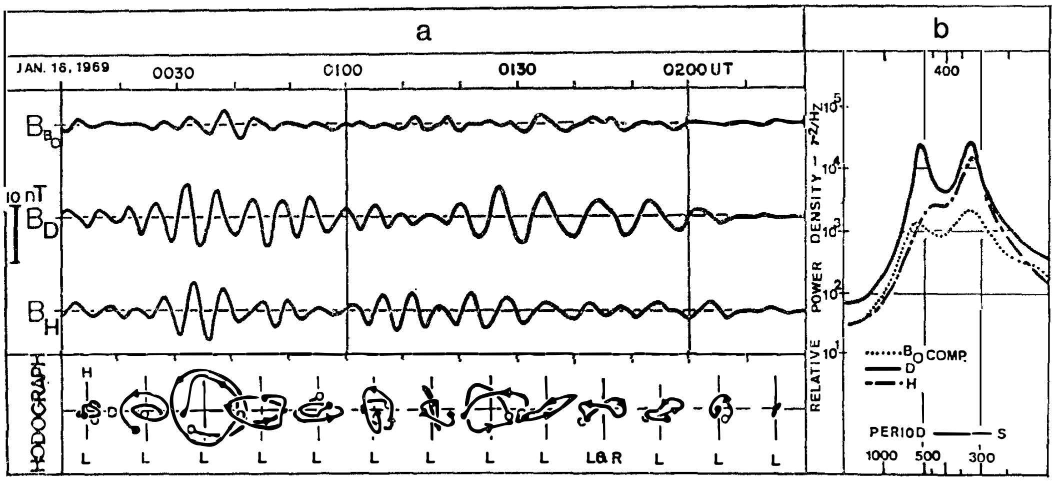



*Fig. 11.* (*a*) *The transferred Pc 5 event from Fig. 10 is represented in the magnetic field coordinates. The hodograph in the H-D plane is also shown in the lower panel.*
(*b*) *Power spectra of the $B_0$-, D-, and H-components are obtained by MEM method.*

amplitudes are large in $D$, *i.e.*, azimuthal direction on the dawn side and in $B_0$, *i.e.*, parallel to the ambient field on the dusk side. The major axes of Pc 5 pulsations in the $H$-$D$ plane are nearly in the $D$-direction (azimuthal mode) on the dawn side and in $H$-direction (radial mode) on the dusk side, respectively. The five curves below are the total power ($\delta B^2_{total}$), power ratios ($P_\perp/P_\perp+P_\parallel$) and ($P_H/P_\perp$), the ellipticity ($\varepsilon$) and the angle ($\theta$) between the major axis and the $D$-axis.

Local time dependence of the variance direction, *i.e.*, the direction of the major

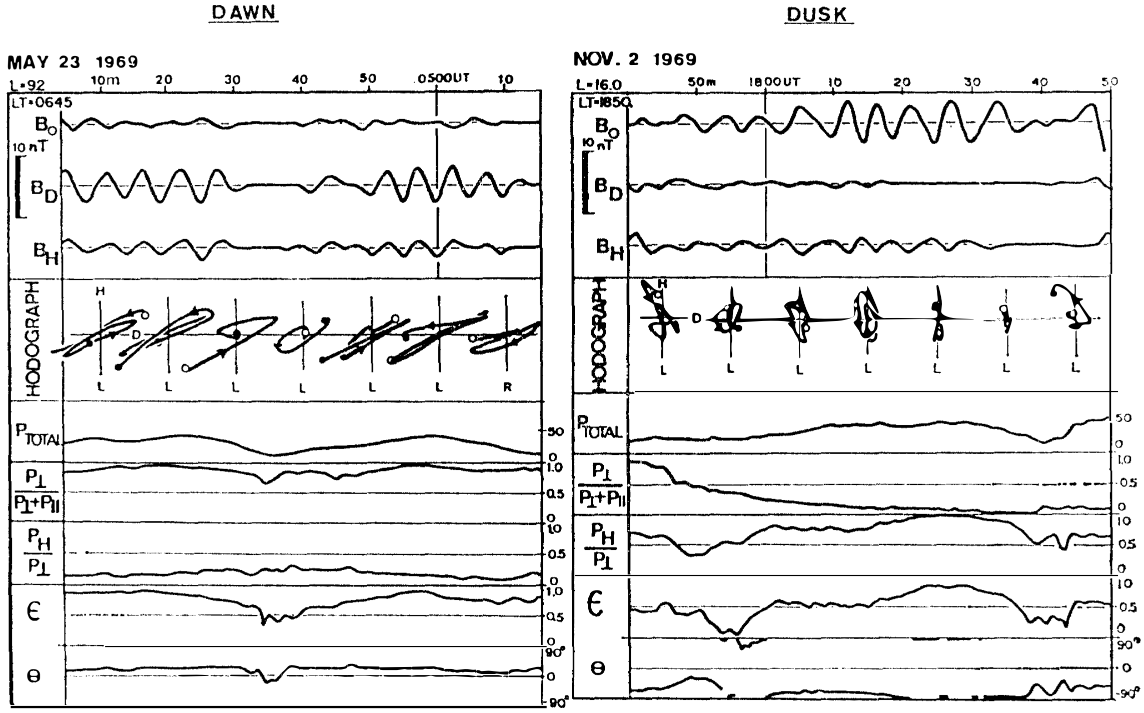


*Fig. 12.* *Two typical examples of time-amplitude Pc 5 pulsations in the magnetic field coordinates in the dawn-side and in the dusk-side magnetosphere, respectively. The five curves in the lower panel express the total power* ($\delta B^2_{\mathrm{total}}$), *power ratios* ($P_\perp/P_\perp+P_\parallel$) *and* ($P_\mathrm{H}/P_\perp$), *the ellipticity* ($\varepsilon$) *and the angle* ($\theta$) *between the major axis and the D-axis, respectively.*

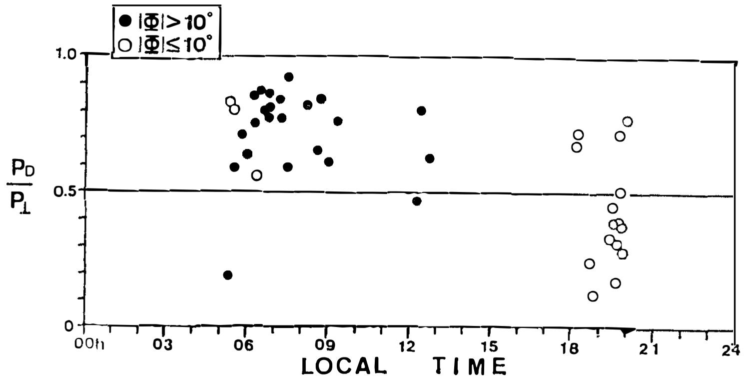


*Fig. 13.* *Local time dependence of variance direction of Pc 5 in the H-D plane. Black and white circles stand for Pc 5 events which were observed by OGO-5 at the higher magnetic latitude and near the magnetic equator, respectively.*

axes of Pc 5 pulsations in the *H-D* plane can be interpreted as a function of the power ratio ($P_\mathrm{D}/P_\perp$) as shown in Fig. 13. We find a strong local time asymmetry in the variance direction of Pc 5 in the magnetosphere, *i.e.*, the azimuthal Pc 5 pulsations dominate in the pre-noon sector and the radial pulsations are mostly observed in the post-noon sector. The relation between the major axis of the perturbation fields in the *H-D* plane and the power ratio of the normal component to the total variance power is represented in Fig. 14 against ($P_\mathrm{D}/P_\perp$) *vs.* ($P_\perp/P_\perp+P_\parallel$). The transverse Pc 5 pulsations in the pre-noon magnetosphere have a significant azimuthal component, and the com-

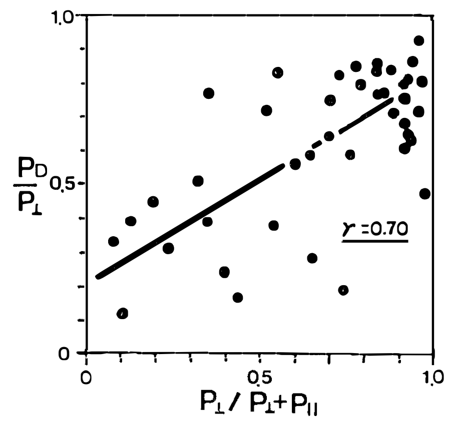



*Fig. 14. Relation between the variance direction in the H-D plane and the variance power in the $B_0$ direction.*

pressional Pc 5 pulsations in the post-noon magnetosphere have a large radial component as compare with the transverse pulsations. The transverse and azimuthal Pc 5 pulsations in the dawn-side magnetosphere and the compressional and radial Pc 5 in the dusk side correspond to the toroidal and poloidal oscillations of a local field line (DUNGEY, 1954; CUMMINGS *et al.*, 1969; YUMOTO *et al.*, 1983), respectively.

SAMSON (1972) showed the diurnal characteristics of the *H-D* components of the Pc 5 events at a line of magnetometer stations extending from 58.5°N to 78°N corrected geomagnetic latitude as shown in Fig. 15a. The diurnal changes in the Pc 5 polarization angles in the *H-D* plane indicated that the polarization was elliptical at the demarcation line with a preference for polarization in the *H*-direction in the interval 0000–0800 UT (1530–2330 local geomagnetic time) and in the *D*-direction in the interval 1200–2000 UT (0330–1130 LGT), respectively. At the lower latitude than the demarcation line the polarization ellipses of Pc 5 pulsations were oriented in the *H*-direction throughout most of the daytime. The latitudinal structure of Pc 5 polarization changes on the ground in the morning is in agreement with the theoretical prediction that a strong azimuthally polarized perturbation including a small radial component in space becomes a radially polarized field across the resonance region (*i. e.*, near the demarcation line) and a azimuthally polarized field at the resonance region on the ground (SOUTHWOOD and HUGHES, 1978). From the top to the lowest panels, Fig. 15b shows North-South profiles of the magnitudes of the horizontal magnetic field components above the ionosphere and the three magnetic field components on the ground, and the phase of the fields on the ground relative to that of $b_x$ above the ionosphere. As only the Alfvén-mode wave is considered to be incident, the magnetic perturbation vector is rotated through 90° in the counterclockwise direction when viewed toward the ground. They also show that large vertical components on the ground can be induced in geomagnetic pulsation signals, because of the localized nature of the source and the requirement of $\nabla \cdot \boldsymbol{b}=0$ in the atmosphere. Recent *in situ* observations of Pc 5 pulsation have been correlated with the ground observations. However, there are two examples of the ground waves having a large amplitude in the *H*-component or in the *D*-component while the wave amplitudes in the dawn-side magnetosphere dominate in the azimuthal component (KOKUBUN, 1980; HILLEBRAND and MCPHERRON, 1980). The compressional and radial waves in the dusk-side magnetosphere have not been identified on

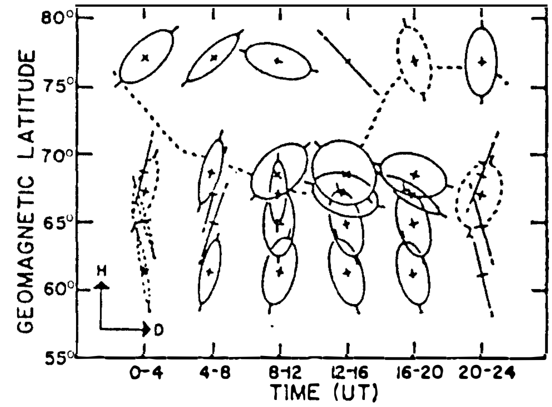



*Fig. 15a.* *Diurnal polarization characteristics of the H-D components of the Pc 5 events at a line of magnetometer stations extending from 58.5°N to 78°N corrected geomagnetic latitude (after* SAMSON, *1972).*

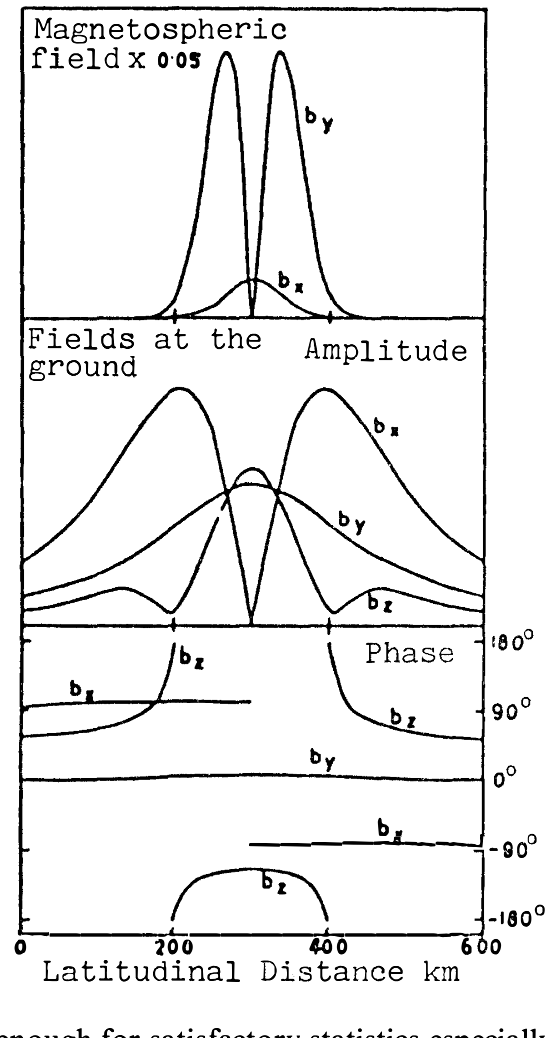



*Fig. 15b.* *The latitudinal structure of Pc 5 polarization. Upper to lower, the magnitudes of the horizontal magnetic field components above the ionosphere, the three magnetic field components on the ground, and the phase of the fields on the ground relative to that of $b_x$ in the magnetosphere (after* SOUTHWOOD *and* HUGHES, *1978).*

the ground. The sample size was not large enough for satisfactory statistics especially concerning the latitudinal structure of Pc 5 polarization. Thus, future observational and theoretical researchs are needed to explain the changes of the variance directions on the ground and in space across the demarcation line and the noon meridian.

The earlier suggestion by KATO and UTSUMI (1964), that the sense of polarization reversed across local noon, was based on uncertain results for post-noon pulsations (see

Fig. 16). A later examination indicates a confused situation, where there is a slight tendency (on a statistical basis), suggesting that for most events a polarization reversal takes place on the ground. SAMSON (1972) demonstrated the diurnal changes in the sense of polarization in the *H-D* component of Pc 5 events observed on the ground as shown in Fig. 17. Satellite observations (see Fig. 18) indicate that the left-handed polarizations and the right-handed polarizations of Pc 5 events dominate in the dawn-side and in the dusk-side magnetosphere, respectively, that is in agreement with the polarization reversal on the ground across the noon meridian. The polarization reversal at

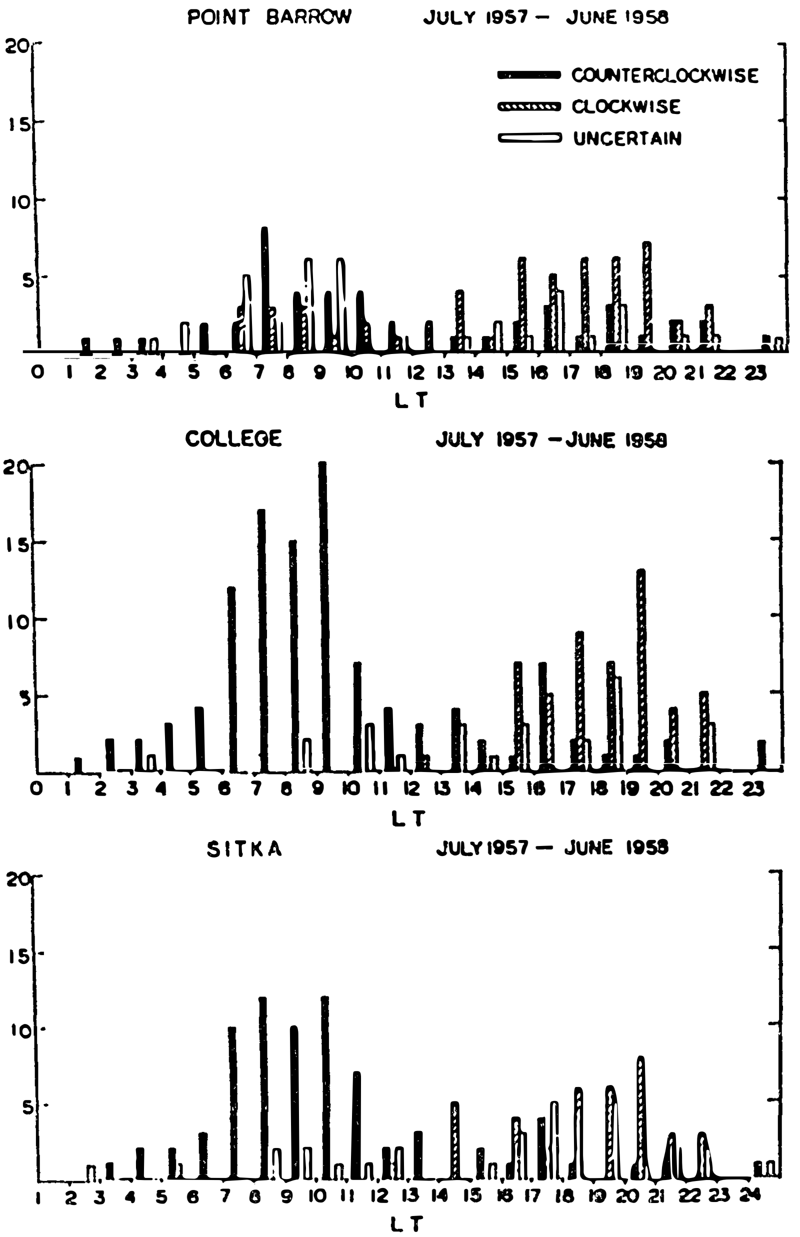



*Fig. 16. Polarizations in the H-D plane for Pc 5 pulsations at a high latitude (Point Barrow), an auroral oval (College), and a sub-auroral zone (Sitka) observatory, respectively (after KATO and UTSUMI, 1964).*

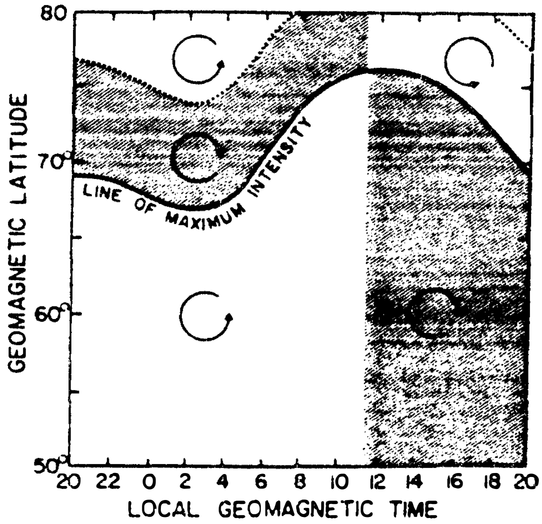



*Fig. 17. The latitudinal and diurnal patterns of the horizontal (H-D) sense of polarization of Pc 5 pulsations (after* SAMSON, *1972).*

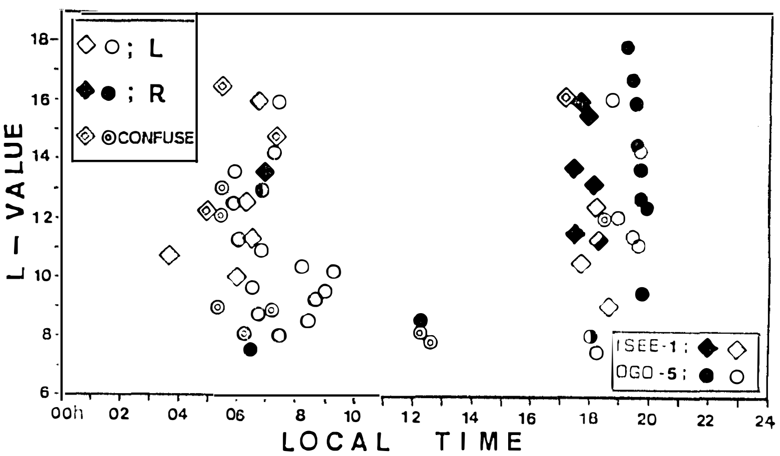



*Fig. 18. Polarization distributions of Pc 5 pulsations in space. A diamond and a circle are Pc 5 pulsations obtained by ISEE-1 and OGO-5, respectively. A white, a black and a doubler indicate the left-handed, the right-handed and the confused polarizations, respectively.*

local noon and the large input of energy at Pc 5 frequencies on the dayside auroral oval (LAM and ROSTOKER, 1978) suggest that the energy of daytime Pc 5 events originates from a Kelvin-Helmholtz instability at the magnetopause (CHEN and HASEGAWA, 1974). However, the latitudinal change in the sense of polarization on the ground, which is marked by the demarcation line (near the maximum intensity curve in Fig. 17), cannot be confirmed in the satellite data. Further study is needed to clarify the simultaneous polarization distribution by means of appropriately separated multi-satellite observations. The observational and theoretical considerations for the latitudinal behavior of Pc 5 pulsations both on the ground and in space are needed to clarify the satellite-ground correlations. The local time asymmetries in the variance direction and the sense of the Pc 5 polarizations in the magnetosphere will be theoretically discussed later, that are strongly associated with the generation mechanism for long-period pulsations at the magnetospheric boundary.

The latitudinal characteristics of Pc 5 frequencies had motivated considerable ex-

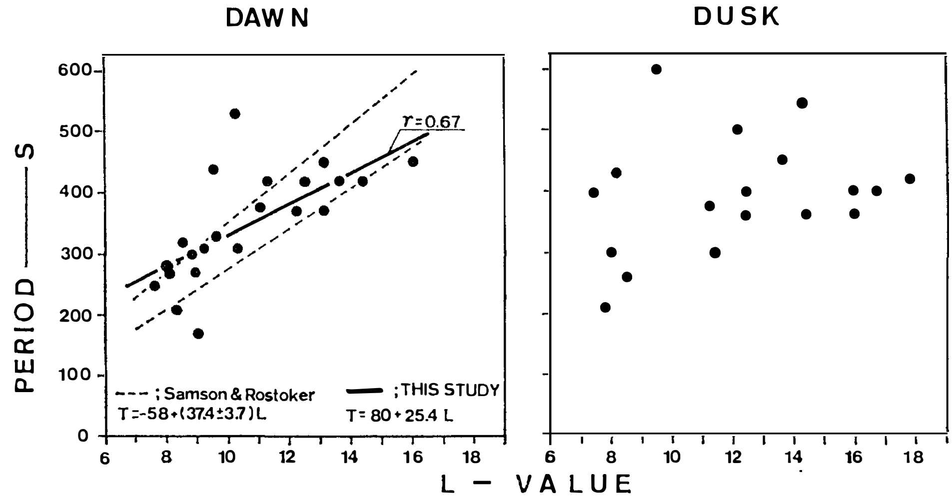



*Fig. 19. L-value dependences of Pc 5 periods observed by OGO-5 in the dawn-side and the dusk-side magnetosphere, respectively.*

perimental and theoretical works in attempts to understand the magnetospheric modes of Pc 5 pulsations. Statistical studies by many worker (OBAYASHI and JACOBS, 1958; OGUTI, 1963; OL', 1963; OBERTZ and RASPOPOV, 1968; VOELKER, 1968) showed that the periods of Pc 5 events on the surface increase with increasing latitude. These results on the ground indicated the possibility that the preferential coupling of energy from an instability driven by the solar wind at the magnetopause into magnetic shells occurs in the inner magnetosphere. SINGER and KIVELSON (1979) indicated that Pc 5 periods in the dawn side of the plasmatrough are generally consistent with the fundamental resonance period. The variations of Pc 5 periods with $L$-shell in both the dawn-side and the dusk-side magnetosphere are summarized in Fig. 19. It is clearly found that the rate of change of Pc 5 period with $L$-values in the dawn-side magnetosphere is approximately the same both with the observational results on the ground obtained by SAMSON and ROSTOKER (1972) and with the theoretical predictions of toroidal eigen-oscillations (WARNER and ORR, 1979). The results of SAMSON and ROSTOKER (1972) discussed were obtained using data from 1969 to 1970, whereas the *in situ* observations by OGO-5 were taken in 1968–1969. Although KATO and SAITO (1964) had shown that the relative sunspot number is an important parameter in determining Pc 5 period, all three years have very similar sunspot numbers and so a comparison is quite straightforward. The Pc 5 pulsations in the dusk-side magnetosphere have larger compressional component (*cf.* Fig. 5) and a poor correlation between the observed periods and the $L$-values. The observational results here thus indicate that energy sources such as the solar wind, or from instabilities at the magnetopause, are coupled into a toroidal eigenmode configuration within the dawn-side magnetosphere, and into a poloidal and compressional penetrating-mode configuration within the dusk-side magnetosphere. The local time asymmetry of the coupling modes with the solar wind sources will be theoretically discussed in the following section.

## 5. Summary and Discussions

In this paper satellite data are analyzed to clarify the characteristics of Pc 5 pulsa-

*Table 3. Summary of the characteristics of Pc 5 obtained by OGO-5 in the magnetosphere.*

| | Spectrum | Dominant-Comp. | | Latitude dependence | Polarization | Period | Dominant mode |
|---|---|---|---|---|---|---|---|
| | Power-$L$ relat. | Inner mag. | Outer mag. | | | $T$–$L$ relat. | |
| | | | | | % | | |
| Morning side | Not clear | $\delta B_{\perp} \gg \delta B_{\parallel}$<br>$\delta B_{D} \gg \delta B_{H}$ | | Middle lat.<br>$10° < \lvert\Phi\rvert < 30°$ | L-handed 66<br>R-handed 7<br>Confused 27 | Clear<br>$T = 80 + 25.4L$ | Alfvén mode |
| Evening side | Power $= C \cdot 10^{0.86L}$ | $\delta B_{\perp} \gg \delta B_{\parallel}$<br>$\delta B_{D} \gg \delta B_{H}$ | $\delta B_{\parallel} \gg \delta B_{\perp}$<br>$\delta B_{H} \gg \delta B_{D}$ | Low lat.<br>$\lvert\Phi\rvert < 10°$ | R-handed 57<br>L-handed 36<br>Confused 7 | Not clear | Alfvén, magneto sonic modes |

tion, which have clues to the generation and propagation mechanisms in the magnetosphere. The ground characteristics of Pc 5 are also reviewed to discuss the correlations with those in space. We can summarize the major results of these analyses, which are tabulated in Table 3, as follows;

(1) The occurrence of Pc 5 in space increases with an increase in the solar wind velocity, that is consistent with the result of the ground observations (Wolfe *et al.*, 1980).

(2) In addition to (1), the most common Pc 5 pulsations in space tend to take place while the IMF is in the Parker spiral direction.

(3) The toroidal modes ($\delta B_{D} \gg \delta B_{H}$) of Pc 5 pulsations are observed at a higher magnetic latitude and a radially localized region of the dawn-side magnetosphere. The compressional and poloidal modes ($\delta B_{\parallel} \sim \delta B_{H} > \delta B_{D}$) of Pc 5 pulsations which continuously penetrate from outside into the inner magnetosphere are mostly observed near the magnetic equator of the dusk-side magnetosphere.

(4) Because the compressional modes with a large horizontal wavenumber on the dusk-magnetosphere are suppressed throughout the atmosphere and the ionosphere (Hughes and Southwood, 1976a, b), the asymmetrical behavior of Pc 5 pulsation activity on the ground across the noon meridian can be explained by the screening effect on the atmosphere and the ionosphere.

(5) The latitudinal changes of the variance directions of Pc 5 on the ground in the morning can be explained by the ionospheric modification of an Alfvénic signals in the magnetosphere (Southwood and Hughes, 1978), although, future researchs are needed for satisfactory statics especially concerning the radial structure of Pc 5 pulsations in space and the latitudinal structure on the ground in the afternoon.

(6) The local time asymmetry in the sense of Pc 5 polarization on the ground is also confirmed in the satellite data. The radial change in the sense of polarization in space has to be clarified by multi-satellite observations in the near future.

(7) The ratio of change of Pc 5 periods with $L$-values on the dawn-side magnetosphere is consistent both with those on the ground (Samson and Rostoker, 1972) and with the theoretical prediction of toroidal eigen-oscillations (Warner and Orr, 1979). Pc 5 pulsations which have a large compressional component in the dusk-side magnetosphere indicate a poor correlation between the observed periods and the $L$-values.

From these results of the observational analyses, we can conclude that Pc 5 pulsations sources from instabilities at the magnetopause or in the solar wind are coupled into a toroidal eigen-oscillation at local field line within the dawn-side magnetosphere, and into a poloidal and penetrating compressional oscillation in the dusk-side magnetosphere.

HUGHES *et al.* (1978) recently showed phase differences between pairs of geostationary satellites (ATS-6, SMS-1 and SMS-2) for Pc 3–5 magnetic pulsations. In the Pc 4–5 ranges the sign of the azimuthal wavenumber changes across local noon and is consistent with phase propagation away from local noon toward the dawn and dusk flanks. By means of data from an east-west array of three ground-based magnetometers separated from each other by about 5° of longitude at geomagnetic latitude $\sim$67°N, OLSON and ROSTOKER (1978) also demonstrated the phase propagation of Pc 4–5 pulsations away from 1100 LT toward the flank sides. These results would appear to provide powerful support for a Kelvin-Helmholtz instability as a source of the pulsation energy (SOUTHWOOD, 1968; CHEN and HASEGAWA, 1974). Daytime ULF pulsations in the Pc 4–5 ranges are thought to be driven by surface waves on the magnetopause where the bulk flow of solar wind has quite a strong velocity shear. Many workers (AUBRY *et al.*, 1971; LEDLEY, 1971; WOLFE and KAUFMAN, 1975; FAIRFIELD, 1976; MAUK *et al.*, 1980; HONES *et al.*, 1981) presented evidence that surface waves of Kelvin-Helmholtz type instabilities exist on the magnetopause. These observational works led to theories of the instability driven by the velocity shear on the magnetospheric boundary (DUNGEY, 1955; SOUTHWOOD, 1968; MCKENZIE, 1970; ONG and RODERICK, 1972; YUMOTO and SAITO, 1980; LEE *et al.*, 1981; WALKER, 1981; MELANDER and PARKS, 1981). However, there is a strong local time asymmetry in the variance direction of Pc 5 in the magnetosphere, *i. e.*, the azimuthal Pc 5 pulsations dominate in the pre-noon sector and the radial and compressional pulsations are mostly observed in the post-noon sector (see Figs. 5 and 13). A more theoretical consideration is therefore required to explain the local time asymmetry in the occurrence of dominant modes of Pc 5 pulsations in the magnetosphere.

In the recent time YUMOTO and SAITO (1980) presented expressions for the polarization of the HM-wave driven by the velocity shear in the magnetospheric boundary layer, where the complexity of the real physical system of the layer was simplified in the paper and analytical study was restricted to shear flow (*i. e.*, $\partial \ln V_0/\partial x \gg \partial \ln \rho_{0m}/\partial x \sim \partial \ln B_0/\partial x$). The ambient magnetic field $B_0(x)$ is parallel to the $z$-axis and the bulk flow $V_{0y}(x)$ of the solar wind in the boundary layer is in the $y$-axis. Thus, the $x$-axis and the $y$-$z$ plane are nearly normal and parallel to the magnetopause, respectively. The perturbation field $\delta A$ in the shear plasmas is modified by the velocity shear term ($\partial V_{0y}/\partial x$) and expressed as follows;

$$\delta A=\delta A_0+f(\boldsymbol{k}, \partial V_0/\partial x)\delta A' , \tag{2}$$

where $\delta A_0$ is the perturbation field in uniform plasmas. For the perturbed magnetic field in first order, the polarization in the $x$-$y$ plane is given by

$$(b_y/b_x)=(v_y/v_x)+i(\partial V_{0y}/\partial x)/\Omega=Re^{i\theta} , \tag{3}$$

where

$$(v_y/v_x)=i[(\Omega^2-\omega_A^2)(\Omega^2-\beta_1\omega_A^2)(\partial \ln \Omega/\partial x)k_y^{-1} -(\Omega^2-\omega_s^2)(V_A^2+V_s^2)k_y(\partial \ln v_x/\partial x)] /(\Omega^2-\omega_+^{L^2})(\Omega^2-\omega_-^{L^2}) ,$$

with

$$\Omega\equiv\omega-k_yV_{0y} , \quad \omega_A^2=V_A^2k_z^2 , \quad \omega_s^2=\beta_1(1+\beta_1)^{-1}\cdot\omega_A^2 ,$$

$$\omega_\pm^{L^2}=\frac{1}{2}(1+\beta_1)V_A^2(k_y^2+k_z^2)\left[1\pm\left\{1-\frac{4k_z^2\beta_1}{(k_y^2+k_z^2)(1+\beta_1)^2}\right\}^{1/2}\right],$$

$$\beta_1=V_s^2/V_A^2 , \quad V_s^2=(\gamma P_0/\rho_{0m}) \text{ and } V_A^2=B_0^2/(\mu_0\rho_{0m}) .$$

The ratio of the transverse component to the total perturbed magnetic field is

$$|b_\perp|^2/|b_{\rm total}|^2=(1+|b_z|^2/|b_\perp|^2)^{-1} , \tag{4}$$

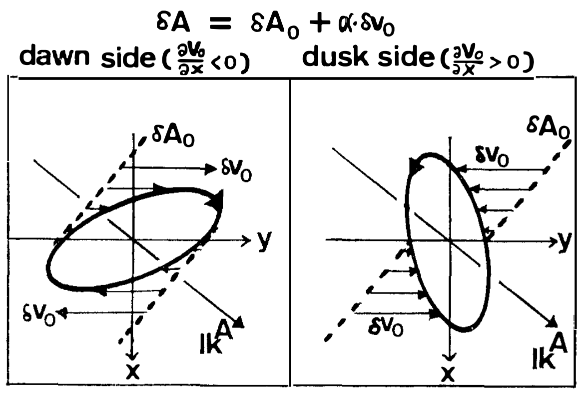
where

$$|b_z|^2/|b_\perp|^2=|i(\partial \ln v_x/\partial x)-k_y(v_y/v_x)|^2k_z^{-2}(1+R^2)^{-1} .$$

A locally-shifted frequency $\Omega$ was introduced. The frequencies of Alfvén wave, the fast and slow magnetosonic waves were represented by $\omega_A$ and $\omega_\pm^L$, respectively. The Alfvén and the sound speeds were also defined as $V_A$ and $V_s$. They demonstrated that a Alfvén-like ($\Omega_A$) HM-wave ($T\gtrsim 40$ s) has sufficient gain to be observed as a HM-wave at the flank-side boundary layer. The sense of polarization and the variance direction of the Alfvén-like ($\Omega_A$) wave are functions of the angle $\phi=\tan^{-1}(k_x/k_y)$ of the $\boldsymbol{k}$-vector and the sign of the velocity shear ($\partial V_{0y}/\partial x \gtrless 0$). When an Alfvénic perturbation, *i.e.*, $\delta \boldsymbol{V}$ and $\delta \boldsymbol{B}\perp \boldsymbol{B}_0$ in an uniform plasma, propagates into the velocity shear plasma as shown in Fig. 20a, the first-ordered perturbation $\delta A$ is polarized by the velocity shear ($\partial V_{0y}/\partial x \gtrless 0$). The dominant polarizations of the Alfvén-like perturbations in the shear plasma are expected to be left-handed and toroidal ($\delta A_y \gg \delta A_x$) mode in the dawn side ($(\partial V_{0y}/\partial x)<0$, $\phi=\tan^{-1}(k_x/k_y)>0$) and right-handed and poloidal ($\delta A_x \gg \delta A_y$) mode in the dusk side ($(\partial V_{0y}/\partial x)>0$, $\phi>0$) boundary layer. They indicated that the $\Omega_A$-wave shows a transverse mode with left-handed polarization in the dawn side and a compressional mode with right-handed polarization in the dusk side boundary layer, whenever signals of Alfvénic modes (DENSKAT and BURLAGA, 1977; BAVASSANO *et al.*, 1981) in the interplanetary medium penetrate into the magnetospheric boundary layer along the Archimedean spiral, *i.e.*, $\phi=\tan^{-1}(k_x/k_y)>0$ as shown in Fig. 20b. The theoretical prediction for ($\phi>0$) is in agreement with the observational results (2), (3) and (6) in the present paper. It is concluded that the local time asymmetry in the occurrence of dominant modes of Pc 5 pulsations can be explained by the Alfvén-like ($\Omega_A$) wave driven by the velocity shear instability (YUMOTO and SAITO, 1980), when signals of Alfvénic waves in the interplanetary medium (BAVASSANO *et al.*, 1981) penetrate into the magnetospheric boundary layer along the Parker spiral direction as illustrated in Fig. 2.

HONES *et al.* (1981) revealed that the pattern of vortical flow has a wavelength of $\sim$20–40 $R_E$ and moves tailward through the magnetosphere at speeds of $\sim$200 km/s. On the other hand, by applying single particle trajectory models to an ion trapping

(*a*)




(*b*)

| ($\Omega_A$-mode) | k-VECTOR | POLARIZATION | VARIANCE DIREC. |
|---|---|---|---|
| DAWN ($\frac{\partial V_0}{\partial x}<0$) | $\phi>0$ | L | $\delta B_\perp >> \delta B_\parallel$ |
| | $\phi<0$ | R | $\delta B_\perp \sim \delta B_\parallel$ |
| DUSK ($\frac{\partial V_0}{\partial x}>0$) | $\phi>0$ | R | $\delta B_\perp \sim \delta B_\parallel$ |
| | $\phi<0$ | L | $\delta B_\perp \gtrsim \delta B_\parallel$ |

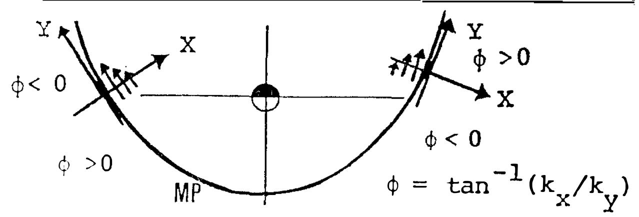



*Fig. 20.* (*a*) *Schematical perturbation field* $\delta A$ *in the shear plasmas. Alfvénic perturbations* ($\delta A_0 \perp k_A$ *and* $B_{IMF}$) *are polarized by the velocity shear* ($\partial V_0/\partial x$) *and become left-handed and* $\delta A_y \gg \delta A_x$(*toroidal*) *in the dawn-side and right-handed and* $\delta A_x \gg \delta A_y$ (*poloidal*) *in the dusk-side boundary layer.*

(*b*) *Theoretical predictions of long-period hydromagnetic waves in the velocity shear plasmas. Polarization and variance directions are functions of the sign of velocity shear* ($\partial V_0/\partial x$) *and the angle of the k-vector* [$\phi = tan^{-1}(k_x/k_y)$].

boundary at the dayside magnetopause, FAHNENSTIEL (1981) demonstrated that longitudinal standing waves occur on the boundary, having typical wavelengths of $\sim 0.5\ R_E$, amplitudes of 0.1 $R_E$, and period of 200–400 s. The results are inconsistent with models of traveling waves moving tailward along the boundary. Therefore, further observational studies of the physical system of the magnetospheric boundary layer are needed to examine the Kelvin-Helmholtz type instabilities and to consider a more realistic mechanism of the long-period magnetic pulsation in the dayside magnetosphere.

## Acknowledgments

We would like to express our sincere thanks to Profs. H. OYA, T. TAMAO, Dr. S. KOKUBUN and Prof. T. HIRASAWA for their valuable discussions and criticisms on our work. We wish also to thank Prof. A. NISHIDA for providing the magnetic field data in space and discussions. The OGO-5 UCLA Triaxial fluxgate magnetometer data of Drs. P. J. COLEMAN, Jr., T. A. FARLEY, C. T. RUSSELL (UCLA), D. L. JUDGE (USC) had been provided by the National Space Science Data Center through the

World Data Center-A for Rockets and Satellites. ISEE-1 and -2 magnetic field summary plots of Prof. C. T. RUSSELL are generated by the UCLA magnetometer group from Decom data tapes.

## References

ARTHUR, C. W. (1978): Pc 4 magnetic pulsations at synchronous orbit, ATS-6. EOS, **59**, 1166.

ARTHUR, C W., MCPHERRON, R. L. and HUGHES, W. J. (1977): A statistical study of Pc 3 magnetic pulsations at synchronous orbit, ATS-6. J. Geophys. Res., **82**, 1149–1157.

AUBRY, M. P., KIVELSON, M. P. and RUSSELL, C. T. (1971): Motion and structure of the magnetopause. J. Geophys. Res., **76**, 1673–1696.

BARFIELD, J. N. and MCPHERRON, R. L. (1972a): Investigation of interaction between Pc 1 and 2 and Pc 5 micropulsations at the synchronous equatorial orbit J. Geophys. Res., **77**, 4704–4719.

BARFIELD, J.N. and MCPHERRON, R. L. (1972b): Statistical characteristics of storm associated Pc 5 micropulsations observed at the synchronous equatorial orbit. J. Geophys. Res., **77**, 4720–4733.

BARFIELD, J. N., MCPHERRON, R. L., COLEMAN, P. J., JR. and SOUTHWOOD, D. J. (1972): Storm-associated Pc 5 micropulsation events observed at the synchronous equatorial orbit. J. Geophys. Res., **77**, 143–158.

BAVASSANO, B., DOBROWOLNY, M., MARIANI, F. and NESS, N. F. (1981): On the polarization state of hydromagnetic fluctuations in the solar wind. J. Geophys. Res., **86**, 1271–1278.

BOSSEN, M., MCPHERRON, R. L. and RUSSELL, C. T. (1976a): Simultaneous Pc 1 observations by the synchronous satellite ATS-1 and ground stations: Implications concerning IPDP generation mechanisms J. Atmos. Terr. Phys., **38**, 1157–1167.

BOSSEN, M., MCPHERRON, R. L. and RUSSELL, C. T. (1976b): A statistical study of Pc 1 magnetic pulsations at synchronous orbit. J. Geophys. Res., **81**, 6083–6091.

CHEN, L. and HASEGAWA, A. (1974): A theory of long-period magnetic pulsations, 1. Steady state excitation of field line resonance. J. Geophys. Res., **79**, 1024–1032.

CUMMINGS, W. D., O'SULLIVAN, R. J. and COLEMAN, P. J., JR. (1969): Standing Alfvén waves in the magnetosphere. J. Geophys. Res., **74**, 778–793.

DENSKAT, K. U. and BURLAGA, L. F. (1977): Multispacecraft observations of microscale fluctuations in the Solar wind. J. Geophys. Res., **82**, 2693–2704.

DUNGEY, J. W. (1954): Electrodynamics of the outer atmosphere. Pa. State Univ., Ionosphere Research Lab., Sci Rep., **69**.

DUNGEY, J. W. (1955): Electrodynamics of the outer atmosphere. The Physics of the Ionosphere. London, Physical Society London, 229–236.

FAHNENSTIEL, S. C. (1981): Standing waves observed at the dayside magnetopause. Geophys. Res. Lett., **8**, 1155–1158.

FAIRFIELD, D. H. (1976): Waves in the vicinity of the magnetopause. Magnetospheric Particles and Fields, ed. by B. M. MCCORMAC. Dordrecht, D. Reidel, 67–77 (Astrophysics and Space Science Library, 58).

GREENSTADT, E. W., MCPHERRON, R. L. and TAKAHASHI, K. (1980): Solar wind control of daytime, midperiod geomagnetic pulsations. J. Geomagn. Geoelectr., **32** (Suppl. II), 89–110.

GUL'ELMI, A. V. (1974): Diagnostics of the magnetosphere and interplanetary medium by means of pulsations. Space Sci. Rev., **16**, 331–345.

GUPTA, J. G. (1976): Some characteristics of large amplitude Pc 5 pulsation. Aust. J. Phys., **29**, 67–79.

HEDGECOCK, P. C. (1976): Giant Pc 5 pulsations in the outer magnetosphere: A survey of HEOS-1 data. Planet. Space Sci., **24**, 921–935.

HILLEBRAND, O. and MCPHERRON, R. L. (1980): Simultaneous observations of magnetic Pc 4 pulsations at the synchronous orbit and on the ground. Submitted to J. Geophys. Res.

HONES, E. W., JR., BIRN, J., BAME, S. J., ASBRIDGE, J. R., PASCHMAN, G., SCHOPKE, N. and HAERENDEL, G. (1981): Further determination of the characteristics of magnetospheric plasma vortices with ISEE 1 and 2. J. Geophys. Res., **86**, 814–820.

HUGHES, W. J. (1974): The effect of the atmosphere and ionosphere on long period magnetospheric micropulsations. Planet. Space Sci., **22**, 1157–1172.

HUGHES, W. J. (1980): Multi satellite observations of geomagnetic pulsations. J. Geomagn. Geoelectr., **32** (Suppl. II), 41–55.

HUGHES, W. J. and SOUTHWOOD, D. J. (1976a): The screening of micropulsation signals by the atmosphere and ionosphere. J. Geophys. Res., **81**, 3234–3240.

HUGHES, W. J. and SOUTHWOOD, F. J. (1976b): An illustration of modification of geomagnetic pulsation structure by the ionosphere. J. Geophys. Res., **81**, 3241–3247.

HUGHES, W. J., MCPHERRON, R. L. and RUSSELL, C. T. (1977): Multiple satellite observations of pulsation resonance structure in the magnetosphere. J. Geophys. Res., **82**, 492–498.

HUGHES, W. J., MCPHERRON, R. L. and BARFIELD, J. N. (1978): Geomagnetic pulsations observed simultaneously on three geostationary satellites. J. Geophys. Res., **83**, 1109–1116.

INOUE, Y. (1973): Wave polarizations of geomagnetic pulsations observed in high latitudes on the earth's surface. J. Geophys. Res., **78**, 2959–2976.

KATO, Y. and UTSUMI, T. (1964): Polarization of the long period geomagnetic pulsation Pc 5. Rep. Ionos. Space Res. Jpn., **18**, 214–217.

KATO, Y. and SAITO, T. (1964): Secular and annual variations in the periods of Pc 3 and Pc 5. Rep. Ionos. Space Res. Jpn., **18**, 183–187.

KING, J. H. (1977): Interplanetary Medium Data Book, Sept. 1977. NSSDC/WDC-A-RES 77–04.

KOKUBUN, S. (1980): Observation of Pc pulsations in the magnetosphere; Satellite-ground correlation. J. Geomagn. Geoelectr., **32** (Suppl. II), 17–39.

KOKUBUN, S. and NAGATA, T. (1965): Geomagnetic pulsation Pc 5 in and near the auroral zones. Rep. Ionos. Space Res. Jpn., **19**, 158–176.

KOKUBUN, S., MCPHERRON, R. L. and RUSSELL, C. T. (1976): Ogo 5 observations of Pc 5 waves: Ground-magnetosphere correlations. J. Geophys. Res., **81**, 5141–5149.

KOKUBUN, S., KIVELSON, M. G., MCPHERRON, R. L. and RUSSELL, C. T. (1977): Ogo 5 observations of Pc 5 waves: Particle flux modulations. J. Geophys. Res., **82**, 2774–2786.

LAM, H. L. and ROSTOKER, G. (1978): The relationship of Pc 5 micropulsation activity in the morning sector to the auroral westward electrojet. Planet. Space Sci., **26**, 473–492.

LEDLEY, B. G. (1971): Magnetopause attitudes during Ogo 5 crossings. J. Geophys. Res., **76**, 6736–6742.

LEE, L. C., ALBANO, R. K. and KAN, J. R. (1981): Kelvin-Helmholtz instability in the magnetopause-boundary layer region. J. Geophys. Res., **86**, 54–58.

MCDIARMID, D. R. and MCNAMARA, A. G. (1973): Radio aurora, storm sudden commencements, and hydromagnetic waves. Can. J. Phys., **51**, 1261–1265.

MCKENZIE, J. F. (1970): Hydromagnetic wave interaction with the magnetopause and the bow shock. Planet. Space Sci., **18**, 1–23.

MAUK, B., GURGIOLO, C., LIN, C. S., PARKES, G. K., ANDERSON, J. A., LIN, R. P. and REME, H. (1980): Surface waves on the magnetopause (abstract). EOS, **61**, 346.

MEKKI, O. M. EL. (1980): Hydromagnetic planetary waves in vertically sheared zonal flow and transverse magnetic field. Sol. Phys., **68**, 3–15.

MELANDER, B. F. and PARKS, F. K. (1981): The effects of cold plasma on the Kelvin-Helmholtz instability. J. Geophys. Res., **86**, 4697–4707.

OBAYASHI, T. and JACOBS, J. A. (1958): Geomagnetic pulsations and the earth's outer atmosphere. Geophys. J. R. Astron. Soc., **1**, 53–63.

OBERTZ, P. and RASPOPOV, O. M. (1968): Study of the spatial characteristics of type Pc 5 geomagnetic pulsations. Geomagn. Aeron., **8**, 424–427.

OGUTI, T. (1963): Inter-relations among the upper atmosphere disturbance phenomena in the auroral zone. JARE Sci. Rep., Ser. A, **1**, 82 p.

OL', A. L. (1963): Long period geomagnetic field pulsations. Geomagn. Aeron., **3**, 113–120.

OLSON, J. V. and ROSTOKER, G. (1978): Longitudinal phase variations of Pc 4–5 micropulsations. J. Geophys. Res., **83**, 2481–2488.

ONG, R. S. B. and RODERICK, N. (1972): On the Kelvin-Helmholtz instability of the earth's magnetopause. Planet. Space Sci., **20**, 1–10.

SAITO, T. (1978): Long-period irregular magnetic pulsation, Pi 3. Space Sci. Rev., **21**, 427–467.

SAITO, T. and YUMOTO, K. (1981): A 15-min period geomagnetic pulsation Ps 6 excited by an instability of auroral electrojets. Relation Between Laboratory and Space Plasmas, ed. by H. KIKUCHI. Dordrecht, D. Reidel, 187–195.

SAMSON, J. C. (1972): Three-dimensional polarization characteristics of high latitude Pc 5 geomagnetic pulsations. J. Geophys. Res., **77**, 6145–6160.

SAMSON, J. C. and ROSTOKER, G. (1972): Latitude-dependent characteristics of high-latitude Pc 4 and Pc 5 micropulsations. J. Geophys. Res., **77**, 6133–6144.

SAMSON, J. C., JACOBS, J. A. and ROSTOKER, G. (1971): Latitude-dependent characteristics of long-period geomagnetic micropulsations. J. Geophys. Res., **76**, 3675–3683.

SINGER, H. J. and KIVELSON, M. G. (1979): The latitudinal structure of Pc 5 waves in space: Magnetic and electric field observations. J. Geophys. Res., **84**, 7213–7222.

SINGER, H. J., RUSSELL, C. T., KIVELSON, M. G., GREENSTADT, E. W. and OLSON, J. V. (1977): Evidence for the control of Pc 3, 4 magnetic pulsations by the solar wind velocity. Geophys. Res. Lett., **4**, 377–379.

SOUTHWOOD, D. J. (1968): The hydromagnetic stability of the magnetospheric boundary. Planet. Space Sci., **16**, 587–605.

SOUTHWOOD, D. J. (1974): Some features of field line resonances in the magnetosphere. Planet. Space Sci., **22**, 483–491.

SOUTHWOOD, D. J. (1979): Magnetopause Kelvin-Helmholtz instability. Magnetospheric Boundary Layer. Paris, ESA SP-148, 357–364.

SOUTHWOOD, D. J. and HUGHES, W. J. (1978): Source induced vertical components in geomagnetic pulsation signals. Planet. Space Sci., **26**, 715–720.

TAMAO, T. (1978): Coupling modes of hydromagnetic oscillations in non-uniform, finite pressure plasmas: Two-fluids model. Planet. Space Sci., **26**, 1141–1148.

UNWIN, R. S. and KNOX, F. B. (1971): Radio aurora and electric fields. Radio Sci., **6**, 1061–1077.

VOELKER, H. (1968): Observations of geomagnetic pulsations; Pc 3, 4 and Pi 2 at different latitudes. Ann. Geophys., **24**, 245–252.

WALKER, A. D. M. (1981): The Kelvin-Helmholtz instability in the low-latitude boundary layer. Planet. Space Sci., **29**, 1119–1133.

WALKER, A. D. M., GREENWALD, R. A., STUART, W. F. and GREEN, C. A. (1978): Resonance region of Pc 5 micropulsation examined by a dual auroral radar system. Nature, **273**, 646–648.

WALKER, A. D. M., GREENWALD, R. A., STUART, W. F. and GREEN, C. A. (1979): Stare auroral radar observations of Pc 5 geomagnetic pulsations. J. Geophys. Res., **84**, 3373–3388.

WARNER, M. R. and ORR, D. (1979): Time of flight calculations for high latitude geomagnetic pulsations. Planet. Space Sci., **27**, 679–689.

WEBB, D. and ORR, D. (1976): Geomagnetic pulsations (5–50 mHz) and the interplanetary magnetic field. J. Geophys. Res., **81**, 5941–5947.

WEBB, D., LANZEROTTI, L. J. and ORR, D. (1977): Hydromagnetic wave observations at large longitudinal separations. J. Geophys. Res., **82**, 3329–3335.

WOLFE, A. and KAUFMAN, R. L. (1975): MHD wave transmission and production near the magnetopause. J. Geophys. Res., **80**, 1764–1775.

WOLFE, A., LANZEROTTI, L. J. and MACLENNAN, C. G. (1980): Dependence of hydromagnetic energy spectra on solar wind velocity and interplanetary magnetic field direction. J. Geophys. Res., **85**, 114–118.

YUMOTO, K. and SAITO, T. (1980): Hydromagnetic wave driven by velocity shear instability in the magnetospheric boundary layer. Planet. Space Sci., **28**, 789–798.

YUMOTO, K. and SAITO, T. (1982): Nonlinear resonance theory of Pc 3 magnetic pulsation. J. Geophys. Res., **87**, 5159–5168.

YUMOTO, K. and SAKURAI, T. (1977): Characteristics of quiet time Pc 5 in the magnetosphere. Abstracts of the 61th General meeting of Japanese Society of Geomagnetim and Geoelectricity,

Tokyo, 1.
YUMOTO, K., EITOKU, A. and SAITO, T. (1983): Hydromagnetic eigen-oscillation in the dipolar field. Mem. Natl Inst. Polar Res., Spec. Issue, **26**, 61–80.

(*Received July 29, 1982; Revised manuscript received October 27, 1982*)