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Pc 3 MAGNETIC PULSATIONS OBSERVED AT LOW LATITUDES: A POSSIBLE MODEL

Kiyohumi YUMOTO[1], Takao SAITO[1] and Yoshihito TANAKA[2]

[1] *Onagawa Magnetic Observatory and Geophysical Institute, Tohoku University, Sendai 980*
[2] *Research Institute of Atmospherics, Nagoya University, Toyokawa 442*

Abstract: It is recently demonstrated that Pc 3 magnetic polarizations observed at equatorial latitudes ($|\Phi|<20°$) are different from those at low-latitude Japan-Australia conjugate stations ($|\Phi|\sim 35°$). In order to interpret the Pc 3 polarization characteristics at lower latitudes ($|\Phi|\lesssim 45°$), we propose a probable, new qualitative model in which two (or more) superimposed ionospheric eddy currents, oscillating with slight differences in frequency in the Pc 3 range and in apparent azimuthal wave number, move azimuthally at low latitudes ($|\Phi|\lesssim 45°$). Near low latitudes of $|\Phi|\sim 45°$ ionospheric rotational Hall currents should be induced by field-aligned currents associated with localized shear Alfvén waves which are excited by compressional Pc 3 source waves near $|\Phi|\sim 45°$. Near the equatorial region ionospheric Pedersen eddy currents may be caused by inductive electric fields of compressional Pc 3 source waves which would propagate from the outer magnetosphere to the equatorial ionosphere.

1. Introduction

Magnetosonic upstream waves in the Pc 3–4 frequency range (15–100 mHz) in the earth's foreshock are believed to be a main source of low-latitude Pc 3 pulsations at $L\sim 1.5$–3.0 (GREENSTADT *et al.*, 1983; RUSSELL *et al.*, 1983; YUMOTO, 1985; YUMOTO *et al.*, 1984, 1985a; WOLFE *et al.*, 1985). The upstream waves of compressional mode can propagate across the ambient magnetic field into the inner plasmasphere, and then can couple with various hydromagnetic oscillations, *e.g.*, a surface eigen-oscillation at the plasmapause (L_{PP}) (CHEN and HASEGAWA, 1974), trapped oscillations of fast magnetosonic waves in the Alfvén trough ($L\sim 1.7$-L_{PP}), fundametal (at $L=1.7$–2.6) and higher-harmonic (at $L\gtrsim 2.6$) standing oscillations of local field lines (see YUMOTO and SAITO, 1983).

However, Pc 3 pulsations at very low latitudes ($|\Phi|<22°$) are not yet sufficiently clarified either observationally or theoretically. KUWASHIMA *et al.* (1979) pointed out that the diurnal variation of Pc 3 polarizations at very low latitude, Chichijima ($\Phi=17.1°$, $\Lambda=208.9°$), is different from that of low-latitude Pc 3's observed simultaneously at Memambetsu (34.0°, 208.4°). SAITO *et al.* (1986) recently reported that Pc 3 polarizations at very low latitudes ($|\Phi|\sim 10°$–$20°$) are predominantly right-handed (left-handed) with major axis in the NW-SE (NE-SW) quadrant in the morning sector in the northern (southern) hemisphere. The sense of Pc 3 polarizations at $|\Phi|\sim 10°$–$20°$ was statistically demonstrated to be opposite to that at the low-latitude conjugate stations of $|\Phi|\sim 35°$, where Pc 3 pulsations in the sunlit morning are predominantly a standing field line-like oscillation with "mirror" polarizations, *i.e.*, being left-handed (right-handed) with major axis in the NW-SE (NE-SW) quadrant in the northern (southern) hemisphere (*cf.* YUMOTO *et al.*, 1985b). On the other hand, it is noteworthy that the maximum height of the lines of force at $|\Phi|<22°$ magnetic latitudes is abuot 1000 km above the ground. The field lines are almost in the ionosphere, where ion-neutral particle collisions are notably frequent than in the magnetosphere, and thus a standing field-line oscillation is difficult (SAKA, 1985). Therefore, a more realistic model is needed to explain the relationship between low-latitude and equatorial Pc 3 pulasations, and to interpret the Pc 3 polarizations observed at lower latitudes ($|\Phi|\lesssim 40°$).

On the basis both of the polarization characteristics of Pc 3 pulsations at lower latitudes (YUMOTO *et al.*, 1985b; SAITO *et al.*, 1986) and recently published theories regarding ionospheric eddy currents induced by hydromagnetic waves (PASHIN *et al.*, 1982; GLASSMEIER, 1984; TAMAO, 1984, 1986), we would like to propose a new qualitative model for the generation mechanism of Pc 3 pulsations at lower latitudes ($|\Phi|\lesssim 45°$) in the present paper.

2. Pc 3 Polarizations at Lower-Latitude Stations

In the present section we will discuss a possibility for standing field-line oscillations at very low latitudes, and will summarize the observed Pc 3 polarizations at lower latitudes ($|\Phi|\lesssim 35°$). Figure 1 shows the magnetic lines of force illustrated as a function of geomagnetic latitude. It is noteworthy that the maximum height of the lines of force at $|\Phi|<22°$ magnetic latitude is about 1000 km above the ground, and then the field lines from $L<1.11$ are almost entirely in the ionosphere. Therefore, a stand-

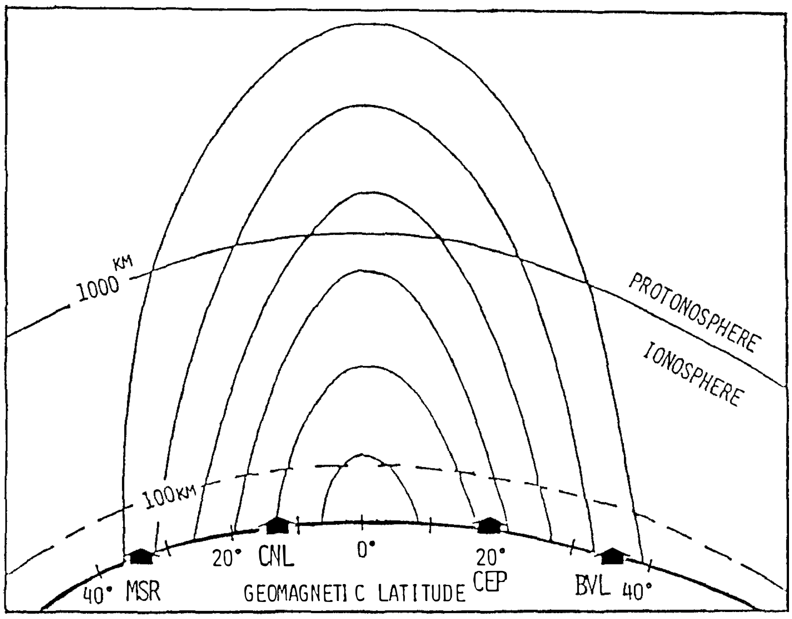

Fig. 1. Schematic illustration of the configuration of geomagnetic lines of force above the earth, as a function of magnetic latitude.

ing field-line oscillation can hardly occur at $|\Phi|<22°$, *i.e.*, $L<1.11$. Characteristics of Pc 3 pulsations at higher magnetic latitudes ($|\Phi|>22°$) should be different from those at lower latitudes ($|\Phi|<22°$). Magnetic variations at lower latitudes cannot be explained using a wave theory in the hydromagnetic region. Hence polarization senses of magnetic variations are given in the present paper by a view looking down onto the earth in each hemisphere.

YUMOTO *et al.* (1985b) demonstrated that there were three distinct intervals in the diurnal variation of Pc 3 polarizations observed at the low-latitude conjugate stations of $|\Phi|\sim 35°$. Before sunrise, the major axes of Pc 3 polarization ellipses associated with coherent *H*- and *D*-wave packets were almost in the NW-SE quadrant at both the northern and southern stations (see Fig. 5 of YUMOTO *et al.* 1985b). In the sunlit ionosphere during 0630–1100 local time (LT), the predominant Pc 3 pulsations showed "mirror" polarizations of standing field line-like oscillations, *i.e.*, being left-handed (right-handed) with the major axis in the NW-SE (NE-SW) quadrant in the northern (southern) hemisphere. In the afternoon, the *D* component amplitude of Pc 3 was often smaller than that in the *H* component and wave packets of the *D* component were not always coincident with those of the *H* component. Therefore, mixed polarizations were observed, but the major axes were almost oppositely directed at the conjugate northern and southern stations. The polarization ellipse changed the major axis orientation in the northern (southern) hemisphere from predominantly NW-SE (NE-SW) in the morning to predominantly NE-SW/NW-SE (NW-SE) in the afternoon sector. Sometimes the polarization reversal across local noon appeared simultaneously at the low-latitude conjugate stations, which is consistent with the earlier works (LANZEROTTI *et al*, 1981; FRASER and ANSARI, 1985). Pc 3 source waves which originate outside the magnetosphere are statistically propagating westward in the morning and eastward in the evening and can couple with various HM oscillations in the plasmasphere.

In order to clarify polarization characteristics of very low-latitude Pc 3's at $|\Phi|\sim 10°–20°$, SAITO *et al.* (1986) analyzed magnetic pulsation data from Chung-Li and Cepu stations during the period of June 1 to 13, 1983. The Pc 3 pulsations at CNL ($\Phi=13.8°$) and CEP ($-18.3°$) were often observed in the morning ($\sim$0600 LT) and near local noon ($\sim$1200 LT) during the interval. They also demonstrated that the diurnal variation of Pc 3 orientation angles at the very low latitudes (CNL, CEP; $|\Phi|\sim 10°–20°$) is consistent with those at the low-latitude conjugate stations (MSR, BVL; $|\Phi|\sim 35°$), except for the sunrise effect (see Fig. 5 of YUMOTO *et al.*, 1985b). The Pc 3 polazrizations at very low latitudes ($|\Phi|\sim 10°–20°$) change from predominantly right-handed (left-handed) with the major axis in the NW-SE (NE-SW) quadrant to predominantly left/right-handed (right/left-handed) with the axis in no specific (NW-SE) quadrant near local noon in the northern (southern) hemisphere. It is noteworthy that although polarization reversal and major axis change near local noon occur concurrently at $|\Phi|\sim 35°$, the polarization senses at the very low latitudes ($|\Phi|\sim 10°–20°$) are found to be opposite to those of Pc 3's at the conjugate stations of $|\Phi|\sim 35°$.

A schematic distribution of Pc 3 polarizations observed at the equatorial and low latitudes in the sunlit hemisphere is illustrated in Fig. 2, as a function of local time and geomagnetic latitudes. The polarization and orientation changes of Pc 3 at $|\Phi|\sim$

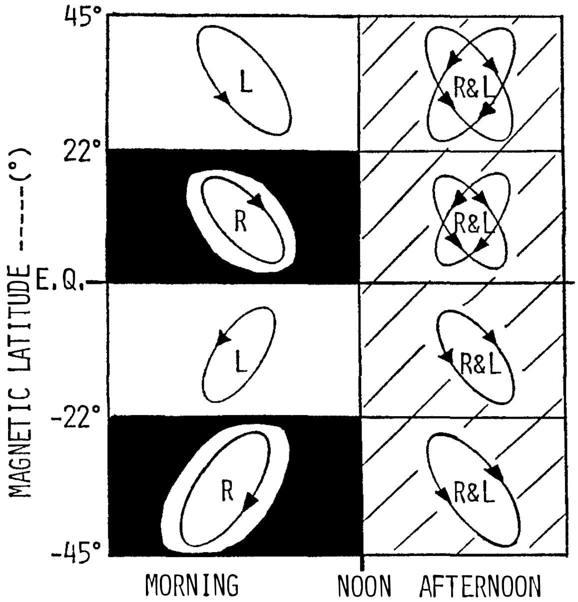

Fig. 2. Local time and latitudinal dependences of Pc 3 polarizations at lower latitudes ($|\Phi| \lesssim 45°$) in the sunlit hemisphere, which are based on the observations of YUMOTO *et al. (1985b) and* SAITO *et al. (1986).*

10°–35° across local noon may be associated with either longitudinal propagation changes or a dawn-dusk asymmetry of predominant mode of Pc 3 source waves in the magnetosphere (HUGHES *et al.*, 1978; SAITO *et al.*, 1984; YUMOTO *et al.*, 1985b). By using the AFGL- and southeast Australia-network pulsation data, SAKA and KIM (1985) and ANSARI and FRASER (1985) recently examined azimuthal wave numbers of Pc 3 pulsations at $|\Phi| \sim 55°$ and 41°–52°, respectively. They found that the longitudinal phase propagation changes statistically from westward in the morning to eastward in the afternoon sector. Thus, Pc 3 source waves in the inner morning- and afternoon-side magnetosphere are believed to propagate in the opposite longitudinal directions. Mixed polarizations of Pc 3's in the afternoon sector may be due to larger horizontal wave number (*cf.* HUGHES *et al.*, 1978; SAITO *et al.*, 1984), however, further observational studies are needed to clarify generation mechanisms for the dawn-dusk asymmetry of low-latitude Pc 3 polarizations. Polarization reversal and orientation angle changes also appeared clearly near the equator and at 22° magnetic latitude in the morning sector. Although the latitudinal dependences of Pc 3 polarizations at $|\Phi| \leq 35°$ are not yet completely understood, we will propose a new qualitative model to interpret the polarization distribution in the next section.

3. Discussion; A Possible Model of Low-Latitude and Equatorial Pc 3

Exogenic Pc 3 source waves hardly excite a standing oscillation of local field lines at very low latitudes ($|\Phi| < 22°$) (*cf.* YUMOTO, 1986). The magnetic lines of force at $|\Phi| < 22°$ are almost in the ionosphere where ion-neutral particle collisions are notably frequent (see Fig. 1). Pc 3 magnetic variations at $|\Phi| \lesssim 22°$ on the ground can theore-

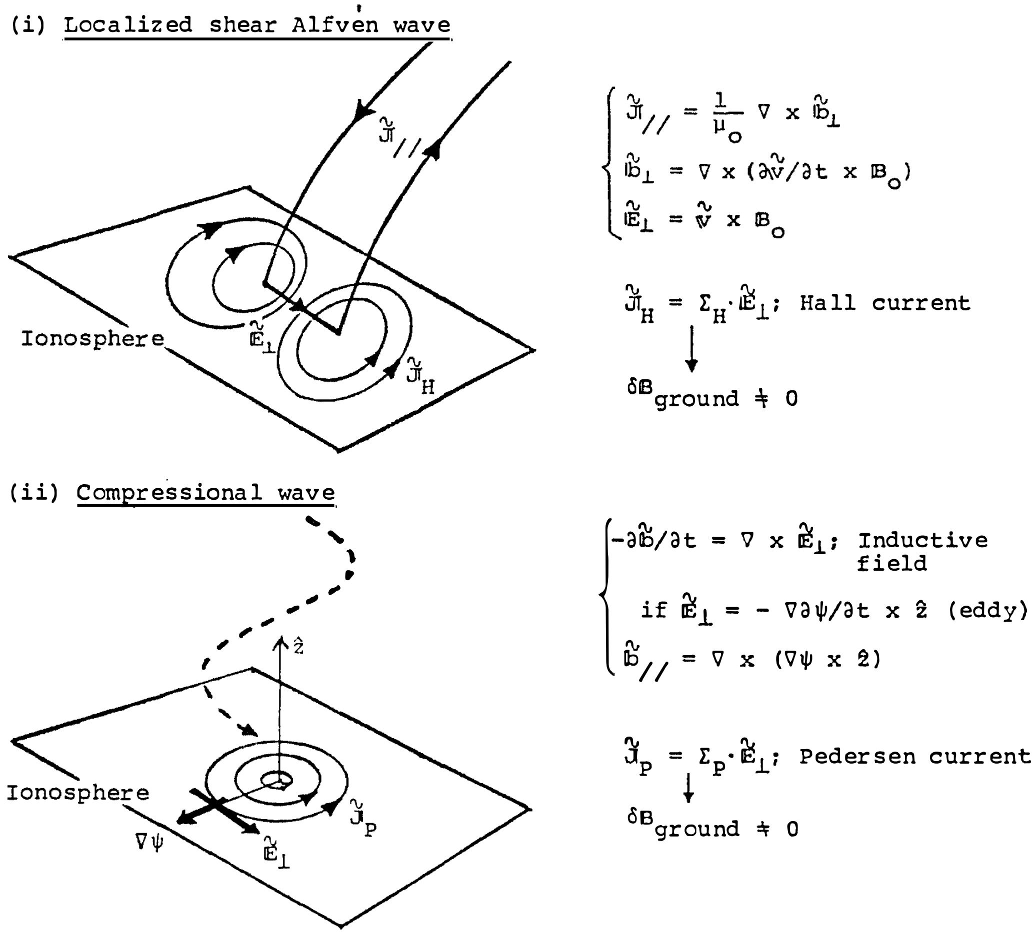

Fig. 3. Ionospheric eddy currents, which are induced by (i) localized shear Alfvén wave and (ii) compressional wave propagating from the magnetosphere into the ionosphere, contribute to magnetic variations on the ground.

tically be considered to be caused by an ionospheric Pedersen eddy current inducted by the inductive electric field of fast magnetosonic Pc 3 source waves (the bottom panel of Fig. 3; *cf.* TAMAO (1984)). If an ionospheric Pedersen eddy current induced by compressional Pc 3's as shown in the left panel of Fig. 4 moves westward in the morning sector and the current strength changes periodically with time, Pc 3 magnetic polarizations at $|\Phi| \lesssim 22°$ on the ground are expected to be right-handed and left-handed in the northern and southern hemisphere, respectively. The theoretical prediction of polarization sense is in good agreement with the statistical results as shown in Fig. 2. The expected phase relation between the northern and southern circular polarizations near the equatorial region is 180° out of phase in the H component and in phase in the D component.

On the other hand, predominant Pc 3 pulsations at the low-latitude conjugate stations of $|\Phi| \sim 35°$ in the sunlit hemisphere may be associated with a standing field-line oscillation at $L \sim 2.0$. An ionospheric rotational Hall (or the source free) current induced by field-aligned current associated with localized shear Alfvén wave (*i.e.*, standing field-line oscillation) contributes to the magnetic field observable on the ground (see the top panel of Fig. 3; *cf.* PASHIN *et al.* (1982), GLASSMEIER (1984), TAMAO (1984,

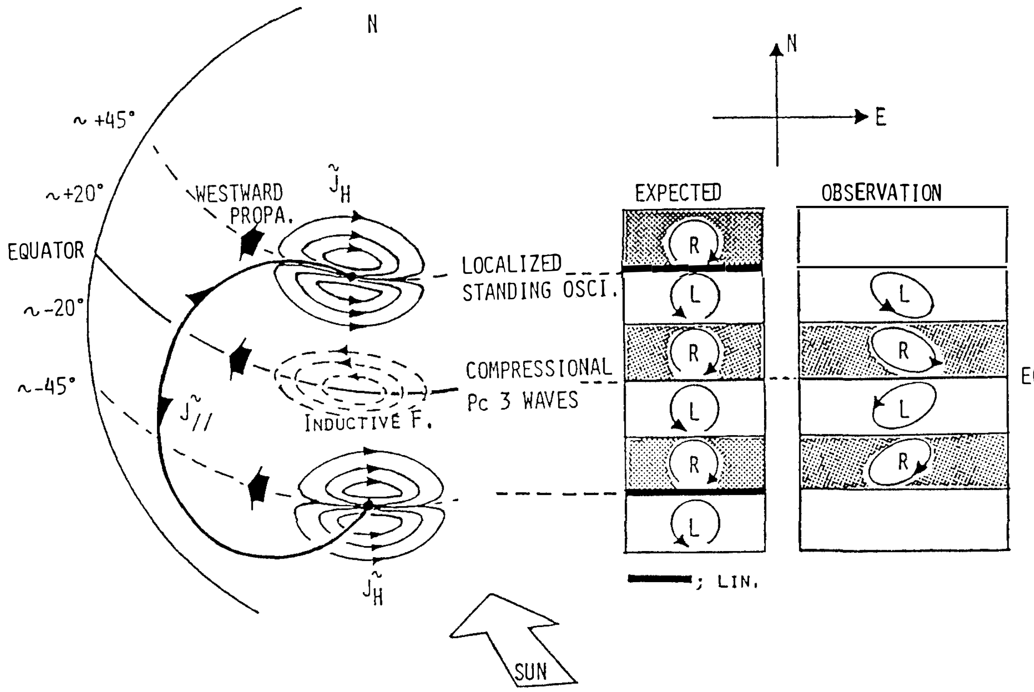

Fig. 4. A possible model of two different type ionospheric eddy currents for the generation mechanism of equatorial and low-latitude Pc 3's in the morning sector. (Left) Two types of current systems represented by solid and dotted lines indicate an ionospheric rotational Hall current associated with a localized field-aligned current of a standing Pc 3 oscillation at $|\Phi| \sim 45°$ *and a Pedersen eddy current induced by an inductive electric field of a compressional Pc 3 wave in the very low-latitude ionosphere* ($|\Phi| \lesssim 22°$)*, respectively. These two ionospheric current patterns and believed to statistically propagate westward in the morning. (Middle) Magnetic polarizations expected from the Pc 3 ionospheric current model on the ground. Open, shaded, and solid-line areas indicate circularly left-handed, circularly right-handed, and linear polarizations, respectively, from a view looking down onto the earth in each hemisphere. (Right) Summary of low-latitude Pc 3 polarizations in the morning sector (cf. Fig. 2).*

1986)). If an ionospheric Hall eddy current pattern associated with Pc 3 standing field-line oscillations at $|\Phi| \sim 45°$ moves westward in the morning sector and the current strength changes periodically with time as illustrated in the left panel of Fig. 4, the expected magnetic polarization in the northern hemisphere becomes right-handed and left-handed at higher and lower latitude side of $L \sim 2.0$, respectively, and vice versa in the southern hemisphere (see the middle panel of Fig. 4). Linear polarization can be also predicted to appear near $L=2.0$. The observed sense of Pc 3 polarizations at the conjugate stations of $|\Phi| \sim 35°$ (Fig. 2) is in agreement with the expected polarization sense.

Pc 3 activity at mid-latitude bears an anticorrelation to increases in F-region electron concentrations (VERÖ and MENK, 1986), while Pc 3 occurrence peak at very low latitudes is consistent with that of the total electron content obtained by satellite differential Doppler measurements (CHAO, private communication, 1985). These observational facts suggest the possibility that Pc 3 pulsations at mid and very low latitudes are associated mainly with an ionospheric eddy Hall current induced by a standing field-line oscillation at $L\sim 2.0$ and with an ionospheric Pedersen eddy current induced by compressional waves at $L\lesssim 1.11$, respectively.

However, the expected polarizations with 90° phase lag between H and D components obtained by the simplified ionospheric eddy current model in the middle panel of Fig. 4, are not in agreement with the observed orientation angles of major axes of elliptical Pc 3 polarizations, as summarized in the right panel of Fig. 4 (or Fig. 2). If the magnetic variation observed on the ground could be caused only by the ionospheric eddy current, a more realistic and/or sophisticated model is needed in order to explain the orientation angles of major axes. As demonstrated in the appendix, any elliptical polarization can be represented approximately as a superposition of two (or more) circularly polarized oscillations moving azimuthally with suitable amplitudes and phase constants. It is reasonable to consider a superposition of the two (or more) "waves", because low-latitude Pc 3 magnetic pulsations tend to show a wave packet-like structure and to have plural dominant frequencies (see Fig. 2 of YUMOTO and SAITO, 1982). For example, a superposition of two circularly polarized oscillations propagating azimuthally with opposite rotational directions ($j_1=1$; right-handed, $j_2=-1$; left-handed), slight differences of angular frequencies (*i.e.*, $\omega_2-\omega_1=\Delta\omega>0$) and of azimuthal apparent wave numbers ($m_2-m_1=\Delta m>0$), and the same amplitudes ($A_1=A_2$), can be given by using (eq. A-3) in the appendix as follows:

$$\boldsymbol{B}=2A\,[\boldsymbol{e}_{\mathrm{H}}\cos(m_1\phi-\omega_1 t+\Delta\theta/2)-\boldsymbol{e}_{\mathrm{D}}|\Delta\theta/2|\cos(m_1\phi-\omega_1 t)]\,, \tag{1}$$

for $|\Delta\theta/m_1\phi-\omega_1 t|\ll 1$ with $\Delta\theta=\Delta m\phi-\Delta\omega t$, where $\boldsymbol{e}_{\mathrm{H}}$ and $\boldsymbol{e}_{\mathrm{D}}$ stand for unit vectors of the H and D components, respectively. Low-latitude Pc 3 pulsations have larger amplitudes in the H component than in the D component, thus, phase lag of $|\Delta\theta/2|$ must be $\lesssim 1$ (*cf.* YUMOTO *et al.*, 1985b). Because individual wave packet-like structures of low-latitude Pc 3 pulsations show slightly different predominant periods (see Fig. 2 of YUMOTO and SAITO, 1982), the superimposed "waves" of eq. (1) can represent one wave-packet structure having parameter of $\Delta m\phi/\Delta\omega\lesssim T_0$ (spacing period of wave packet). Superimposed "waves" with $0<\Delta\theta<2$ and $-2<\Delta\theta<0$ can show elliptical polarizations, being similar to Pc 3 right- and left-handed polarizations in the NW-SE quadrant at $\Phi>22°$ and at $0°<\Phi<22°$, respectively, as shown in Fig. 2.

Elliptical Pc 3 polarizations observed on the ground near the equatorial (at low latitudes) in the morning sector may be explained by the opposite propagation of two superimposed ionospheric Pedersen (Hall) eddy currents induced by inductive electric fields of compressional Pc 3 waves near the equator (by field-aligned currents of localized shear Alfvén waves excited predominantly at $|\Phi|\sim 45°$). However, Pc 3 magnetic pulsations observed at $|\Phi|\sim 40°$–$55°$ tend to have *statistically* a westward wave number in the morning and an eastward one in the afternoon magnetosphere (*cf.* ANSARI and FRASER, 1985; SAKA and KIM, 1985). Another possiblility is a superposition of the ionospheric Pedersen and Hall eddy currents, which move in the same westward direction and make right-handed and left-handed polarization, respectively, in morning sector in the northern hemisphere.

However, we cannot precisely determine the relationship among the superimposed two ionospheric eddy currents, the theoretically predicted, circularly polarizations, and the observed elliptical Pc 3 polarizations on the ground, because measurements of "wave" parameters (dominant frequencies, apparent azimuthal wave numbers, polarizations, phase, amplitudes, etc.) obtained simultaneously at separated stations are insufficient. The ionospheric eddy current model for lower-latitude Pc 3's will be examined by clarifying phase relations between H and D components of pulsations observed at stations which are separated latitudinally and longitudinally. Further theoretical studies and coordinated observations at separated chain stations are needed to clarify characteristics of elliptical Pc 3 pulsations at lower magnetic latitudes ($|\Phi|<45°$), and then to understand completely the propagation and generation mechanism of low-latitude Pc 3 magnetic pulsations.

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Appendix

A general polarization state of a traveling wave can be represented as a superposition of two circularly polarized components with suitable amplitudes and phase constants. Two circularly polarized waves propagating azimuthally in the H-D plane are given by

$$\boldsymbol{B}_1=A_1[\boldsymbol{e}_{\rm H}\cos(m_1\phi-\omega_1 t)+j_1\boldsymbol{e}_{\rm D}\sin(m_1\phi-\omega_1 t)]\,, \tag{A-1}$$

$$\boldsymbol{B}_2=A_2[\boldsymbol{e}_{\rm H}\cos(m_2\phi-\omega_2 t)+j_2\boldsymbol{e}_{\rm D}\sin(m_2\phi-\omega_2 t)]\,, \tag{A-2}$$

where A_n, m_n, ω_n and j_n with $n=1$ and 2 indicate wave amplitude, azimuthal wave number, wave frequency, and polarization sense (*i.e.*, $j_n=1$; right-handed, -1; left-handed), respectively. The superposition of the two waves can be represented by

$$\boldsymbol{B}=\boldsymbol{B}_1+\boldsymbol{B}_2=A\boldsymbol{e}_{\rm H}\cos(m_1\phi-\omega_1 t+\delta)+B\boldsymbol{e}_{\rm D}\sin(m_1\phi-\omega_1 t+\phi)\,, \tag{A-3}$$

with

$$A=[A_1^2+A_2^2+2A_1A_2\cos(\Delta m\phi-\Delta\omega t)]^{1/2}\,,$$

$$\tan\delta=A_2\sin(\Delta m\phi-\Delta\omega t)/[A_1+A_2\cos(\Delta m\phi-\Delta\omega t)]\,,$$

$$B=[A_1^2+A_2^2+2(j_1j_2)A_1A_2\cos(\Delta m\phi-\Delta\omega t)]^{1/2}\,,$$

$$\tan\phi=j_2A_2\sin(\Delta m\phi-\Delta\omega t)/[j_1A_1+j_2A_2\cos(\Delta m\phi-\Delta\omega t)]\,,$$

$$\Delta m=m_2-m_1\,,\quad\text{and}\quad\Delta\omega=\omega_2-\omega_1\,.$$