A VIABLE SOURCE OF LOW-LATITUDE Pc 3'S IN THE MAGNETOSPHERE

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***Abstract*:** Daytime magnetic pulsations observed at synchronous orbit by GOES 2 are analyzed to determine whether there is a candidate for the source of low-latitude Pc 3's in the outer magnetosphere. Compressional, radially transverse, and azimuthally transverse modes of magnetic pulsations in a wide frequency range exist simultaneously in the outer daytime magnetosphere. The compressional and the transverse modes of the daytime magnetic pulsations observed at GOES 2 are statistically dominant in the Pc 3 and in the Pc 4 frequency ranges, respectively. Some 70 percent of the compressional Pc 3 pulsations at GOES 2 have periods similar to the low-latitude Pc 3's observed at San Gabriel Canyon, which is located $\sim 11°$ west of GOES 2's longitude at $L=1.8$. The transverse Pc pulsations at GOES 2 can propagate only into the high-latitude ionosphere. The compressional Pc 3 pulsations at GOES 2 are theoretically expected to propagate across the ambient magnetic field to very low latitudes and to couple with one or more of the followings; (i) a surface wave at the plasmapause (L_{PP}), (ii) a trapped oscillation of the fast magnetosonic wave in the plasmasphere ($L=1.7 \sim L_{PP}$), (iii) a higher-harmonic standing oscillation of a local field line at mid-latitudes ($L=2.0 \sim L_{PP}$), and (iv) a fundamental standing oscillation at very low latitudes ($L=1.1$ and 1.7–2.6). Although further research is needed to clarify the wave and propagation characteristics of the low-latitude Pc 3 pulsations, we believe that the compressional Pc 3 magnetic pulsations in the outer magnetosphere are a source of the low-latitude Pc 3 magnetic pulsations.

1. Introduction

Statistical studies of daytime Pc 3 magnetic pulsations have been extensively made for many years (*cf.* the reviews of KATO and WATANABE, 1957; TROITSKAYA and GUL'ELMI, 1967; SAITO, 1969; JACOBS, 1970; ORR, 1973; LANZEROTTI and FUKUNISHI, 1974; GREENSTADT *et al.*, 1980; HUGHES, 1980; GREEN, 1981). In recent years, ground magnetometer arrays at mid- and high-latitudes have contributed well towards the understanding of continuous pulsations. The work of the Bell Laboratory group (LANZEROTTI and FUKUNISHI, 1974, 1975; FUKUNISHI and LANZEROTTI, 1974a, b) and the result from the IGS array in Northern Europe and Iceland (HANSON *et al.*, 1979) indicated switching in the sense of polarization on each side of the latitude where peak amplitude is observed, and across local noon. These observations support the theory that mid- and high-latitude magnetic pulsations are field line resonance oscillations in the magnetosphere excited by surface waves at the magnetopause (CHEN and HASEGAWA, 1974a, b; SOUTHWOOD, 1974). LANZEROTTI *et al.* (1981) investigated the polarization characteristics of Pc 3 magnetic pulsations at low geomagnetic latitude ($L\sim1.9$). Statistically, the polarization at low latitude was predominantly left-handed in the local morning hours and right-handed in the local afternoon, *i.e.*, the switching of polarization sense across local noon was consistent with the results of Pc 3 pulsations at mid- and high-latitudes. However, the existence of the waves at very low latitude places constraints on the damping rate of externally excited surface waves driven by shear flow instabilities at the magnetospheric boundary (SOUTHWOOD, 1979; YUMOTO and SAITO, 1980). Linear resonance theory for Pc pulsations in the magnetosphere cannot readily incorporate these low-latitude results (LANZEROTTI *et al.*, 1981; SAITO *et al.*, 1981). It has not yet been confirmed whether a source of low-latitude Pc 3's is related to high-latitude Pc 3's, because of difficulties in timing accuracy of widely spaced observations and magnetometer sensitivity. Therefore, further observations of simultaneous correlations between Pc 3 pulsations at high- and low-latitudes, *i.e.*, outside and inside the plasmapause, are needed to identify the source of low-latitude Pc 3's in the outer magnetosphere and to explain the propagation and excitation mechanisms of Pc 3 magnetic pulsations in the magnetosphere.

ARTHUR *et al.* (1977) reported the results of a study designed to determine statistically the nature and variation of the polarization parameters of Pc 3's at synchronous orbit ($L=6.6$). The main characteristics determined are summarized as follows; there are two distinct classes of Pc 3 pulsations at ATS 6. The azimuthal class is linearly polarized and transverse to the ambient magnetic field $\boldsymbol{B}_0$; over 75% of azimuthal events show $85°\lesssim\psi=\cos^{-1}(\hat{B}_0\cdot\hat{b})\lesssim90°$, where $\boldsymbol{b}$ expresses the perturbation field of Pc 3 magnetic pulsations. The radial events are just as linear as the azimuthal class, but most of the events in this class have significant compressional components ($\psi_{peak}\sim70°$), which may be associated with propagating compressional waves in the Pc 3 frequency range in the outer magnetosphere (SATO and FUKUNISHI, 1981; YUMOTO and SAITO, 1982, 1983; YUMOTO *et al.*, 1984). Although the characteristics of Pc 3 pulsations in the magnetosphere have been studied extensively using observations at synchronous orbit (ARTHUR and MCPHERRON, 1975, 1977a, b; HUGHES *et al.*, 1978; PATEL *et al.*, 1979; TAKAHASHI and MCPHERRON, 1982), ground-satellite correlations of these Pc 3 pulsations are not yet well confirmed.

In this paper, we will demonstrate the wave characteristics of magnetic pulsations observed at synchronous satellite GOES 2 ($L=6.67$), and determine whether there is a clear candidate for the source of low-latitude Pc 3's in the outer magnetosphere. In Section 2 we will show simultaneous records of Pc 3 pulsations at GOES 2 and at low-latitude ground station, San Gabriel Canyon (34.2°N, 118.0°W), which is located $\sim11°$ west of GOES 2's longitude at $L=1.8$. These observations will be used to clarify the relation of magnetic pulsations observed outside the plasmapause to the low-latitude Pc 3 pulsations on the ground. In Section 3 we then discuss theoretically how these observations can be deduced from the characteristic frequency of hydromagnetic waves in the geomagnetosphere.

2. Magnetic Pulsations at GOES 2 and at Low-Latitude SGC

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; ARTHUR *et al.*, 1977; HUGHES *et al.*, 1978; KOKUBUN, 1980; YUMOTO and SAITO, 1980; YUMOTO *et al.*, 1983b). The Pc 3–5 pulsations are classified mainly into the two types, azimuthally and radially polarized pulsations, according to the orientation of the wave ellipse. These azimuthal and radial pulsations mostly have transverse and compressional components, respectively (see Fig. 4 of ARTHUR *et al.* (1977) for Pc 3, Fig. 6(d) of ARTHUR and MCPHERRON (1981) for Pc 4, and Fig. 7 of YUMOTO *et al.* (1983b) for Pc 5, respectively). We analyze GOES 2 magnetic data in this section to clarify a relation between dominant modes and characteristic frequencies of hydromagnetic waves outside the plasmapause. Low-latitude ground data near the GOES 2 meridian are also analyzed to examine the satellite-ground correlation of Pc 3 magnetic pulsations.

The Geostationary Operational Environment Satellites (GOES 1, GOES 2, etc.) all lie in geosynchronous orbit (6.67 R_E) and carry on board the Space Environment Monitor (SEM) experiment package (SMS/GOES user documentation by WILKINSON, WDCA, 1982). The SEM contains a twin fluxgate spinning sensor that allows reconstruction of the Earth's magnetic field in three components at geostationary altitude. The basic sensitivity of the magnetometer is 0.2 nT and the time resolution is 3.06 s. The GOES 2 data used in this study were provided by the National Space Science Data Center through the World Data Center A for Rocket and Satellites. The three-component analog magnetograms from GOES 2 on 35 mm microfilm are used from the interval January 27 to February 16, 1981. On the other hand, high-sensitivity, low-latitude ground data which were obtained at a station near the GOES 2 meridian during the period from January 19 to February 21, 1981 are used for the ground-satellite correlation of Pc 3 magnetic pulsations. GOES 2 was located at 106.4°–106.7° west longitude during the interval. The ground data are from the Circum-Northern Pacific ULF Observation Project (SAITO *et al.*, 1981). The magnetic pulsation signals were measured by means of the rulfmeter (Ring-core fluxgate ULF magnetoMETER) along three orthogonal geomagnetic axes. The rulfmeters were transported to the United States and used successfully at three stations, College 64.9°N, 147.8°W), San Gabriel Canyon (34.2°N, 118.0°W), and Ewa Beach (21.4°N, 158.1°W) from January 19 to February 21, 1981. In this study, we use only the SGC magnetic data for comparison with the compressional Pc 3 events at GOES 2, since magnetic signals in the Pc 3 band in the magnetosphere are coherent over at least 20° of longitude (HUGHES *et al.*, 1978). Magnetic variations in the frequency range from 10 Hz to DC can be detected by the rulfmeter, which has a noise level of 0.036 nT rms noise equivalent being comparable with those of the UCLA fluxgate magnetometer (GORE, 1974) and the Imperical College fluxgate magnetometer (HEDGECOCK, 1975). The magnetic signals were registered on magnetic cassette tapes by an analog FM data recorder with an extremely low speed (0.18 mm/s). The analog pulsation signals for 8 days per one cassette tape are reproduced with the speed-up ratio of 254 times of the recording speed. The amplitude and time resolution of the reproduced magnetic data are 0.07 nT and 0.5 s, respectively. Because of trouble with the cassette tape recorder, the *D*-component of magnetic data at SGC could not be reproduced with high resolution. The three-component (*HP*, *HE*, *HN*) analog magnetograms

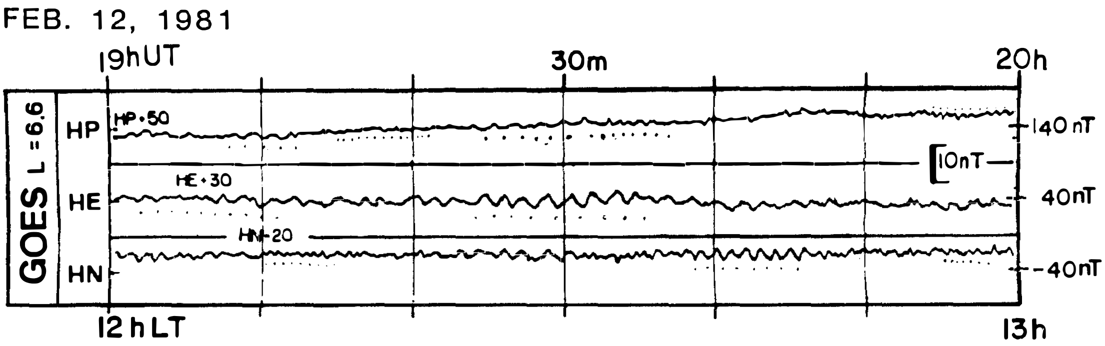

Fig. 1. Daytime magnetic pulsations observed at GOES 2 on February 12, 1981. The magnetic perturbations in the HP, HE and HN directions approximate to the total, radial and azimuthally westward-components of magnetic pulsations near the magnetic equator, respectively. A compressional, a transverse radial and a transverse azimuthal modes in a wide frequency range occur simultaneously at synchronous orbit (L=6.6).

at GOES 2 and the two-component (H, Z) analog magnetograms at SGC during the period from January 27 to February 16, 1981 were expanded and digitized with an automatic digitizer with a sampling period of 5.0 s. The magnetic data at SGC were filtered to remove long-period trends. The digitized data were subjected to power spectral analysis.

Wave characteristics of magnetic pulsations observed by GOES 2 are first studied to examine the relation between dominant modes and characteristic periods in the outer magnetosphere. Figure 1 indicates an example of time-amplitude records of selected events obtained at GOES 2, the orbit of which was in the local noon sector for one hour from 1900 to 2000 UT on February 12, 1981. The three-component analog magnetograms of GOES 2 are plotted in HP, HE, HN coordinates. The HP axis is taken parallel to the spin axis of the satellite, which is nearly perpendicular to the solar-ecliptic plane. The HE axis is radially inward toward the center of the Earth through the satellite. The HN axis is defined by $\boldsymbol{HN}=\boldsymbol{HP}\times\boldsymbol{HE}$. Therefore, the HP-, HE- and HN-components approximately give the total, radial and azimuthally westward-components of magnetic pulsations near the magnetic equator, respectively. Magnetic pulsations whose amplitudes are large in the HP, HE and HN directions can be categorized as a compressional (δB), a transverse radial (δB_{H}) and a transverse azimuthal (δB_{D}) modes, respectively. It is noteworthy that various modes of magnetic pulsations in a wide frequency range exist simultaneously in the outer magnetosphere and dominant periods of the magnetic pulsations in the three-component analog magnetograms are different from one another as shown in Fig. 1. A compressional mode in the Pc 3 frequency range, a transverse radial and a transverse azimuthal modes in the Pc 3–4 range occur simultaneously at synchronous orbit. This observational fact is in agreement with the previous result that magnetic pulsations in a wide frequency range occur simultaneously in closely neighboring regions of the magnetosphere, obtained by multi-satellite observations (SINGER *et al.*, 1979).

Local-time dependence of the occurrence of dominant modes of magnetic pulsations observed at GOES 2 is represented as a function of dominant period of the magnetic pulsations in Fig. 2, where the dominant period is defined as the highest

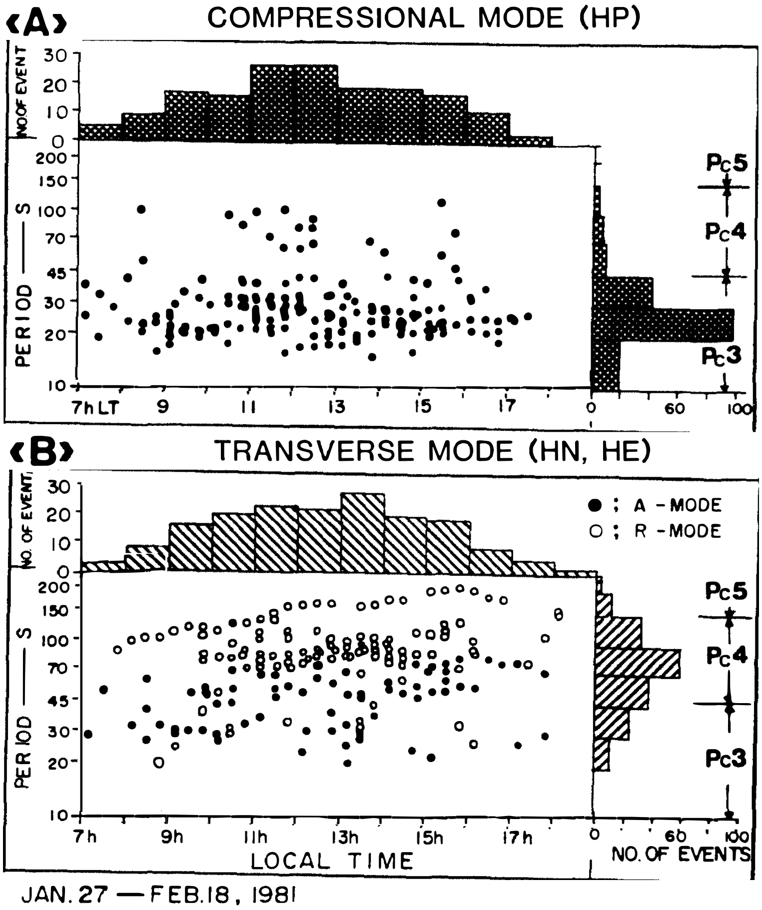

Fig. 2. Relation of dominant periods to dominant modes of daytime magnetic pulsations observed at synchronous orbit (L=6.6). The compressional and transverse modes, which have larger amplitudes in the HP and (HE, HN) directions, are dominant in the Pc 3 and Pc 4 frequency ranges, respectively. Solid and open circles in the lower panel show the azimuthally and radially transverse modes, respectively.

spectral peak in the Pc 3–5 frequency range in each 20 min time interval of the *HP*, *HE* and *HN* analog magnetograms as shown in Fig. 1. The details of the procedure used to determine the pulsation frequency of the daytime Pc 3–5 magnetic pulsations are given in the paper of Yumoto and Saito (1983). We counted as an event a pulsation with amplitude larger than 0.2 nT in each 20 min time interval. The selected events of dominant modes are primarilly daytime phenomena with an occurrence peak near local noon. It is found that the compressional ($\delta B(HP)$) and transverse ($\delta B(HE, HN)$) modes of daytime magnetic pulsations at synchronous orbit (L=6.67) are statistically dominant in the Pc 3 and Pc 4 frequency ranges, respectively. The transverse radial ($\delta B(HE)$) and azimuthal ($\delta B(HN)$) modes are expressed by open and solid circles in Fig. 2B, respectively. Arthur *et al.* (1977) summarized the statistically determined characteristics of magnetic pulsations in the Pc 3 frequency range observed at ATS 6 synchronous orbit. There are two distinct classes of Pc 3 (azimuthal and radial). The radial class in the Pc 3 frequency range shows no discernible local-time frequency dependence and occurs in the daytime, which is consistent with the distribution of the compressional waves ($\delta B(HP)$) at GOES 2 as shown in Fig. 2A. On the other hand, the low-frequency azimuthal class (LA; ~0.035 Hz) is primarily a local morning phenomenon with an occurrence peak in midmorning (~08 LT) and the high-frequency azimuthal class (HA; ~0.055 Hz) occurs near noon. Although the transverse dominant modes in the Pc 3–5 range observed at GOES 2 show an occurrence peak in the noon sector (Fig. 2B), the A-mode ($\delta B(HN)$) in the Pc 3 frequency range dominantly occurs in the morning, that is also in agreement with the statistical characteristics of the LA-modes observed at ATS 6. The transverse radial modes at GOES 2 must be standing eigen-oscillations of poloidal modes, which were recently studied by means of ATS 6 data (TONEGAWA, 1982). The transverse azimuthal modes must be associated with the higher harmonic structure of toroidal modes of TAKAHASHI and MCPHERRON (1982). These transverse modes of magnetic pulsations outside the plasmapause are radially localized and propagate into only the high-latitude ionosphere. The transverse modes at synchronous orbit cannot couple directly with low-latitude magnetic pulsations. On the other hand, the compressional Pc 3 magnetic pulsations in the outer magnetosphere can propagate across the ambient magnetic field into the inner magnetosphere and can couple with surface waves at the plasmapause (CHEN and HASEGAWA, 1974b), trapped oscillations in the plasmasphere (TAMAO, 1978), and eigen-oscillations of local field lines at mid- and low-latitude, which will be theoretically discussed later.

The relation of the compressional Pc 3 pulsations at GOES 2 to low-latitude Pc 3 pulsations is now examined by comparing the dominant periods of Pc 3 magnetic pulsations at both locations. The ground data used in this study are from the Circum-Northern-Pacific ULF Observation Project (SAITO *et al.*, 1981, 1983). In this study,

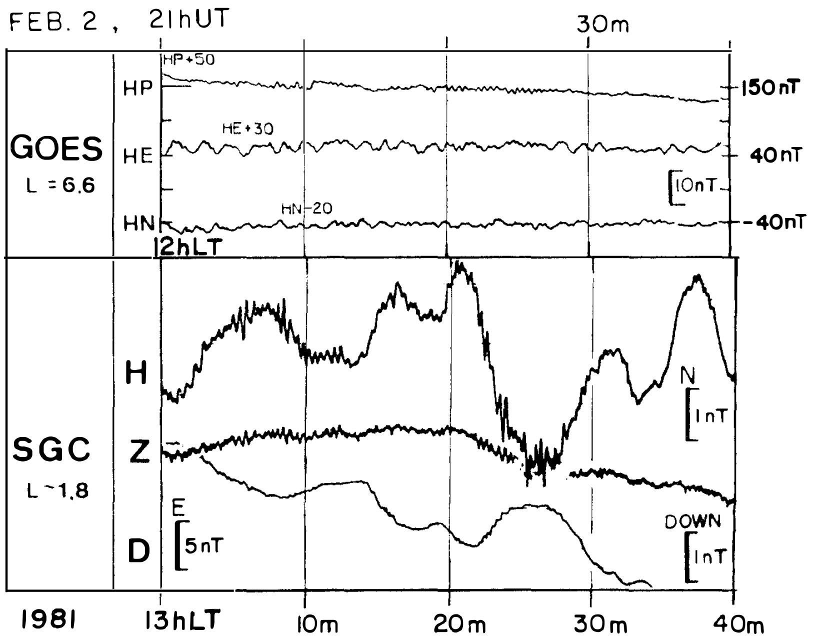

Fig. 3. Simultaneous records of daytime magnetic pulsations observed at GOES 2 (L=6.6) and SGC station, which is located ~11° west of GOES 2's longitude at L~1.8, on February 2, 1981.

we used only the SGC magnetic data for comparison with the compressional Pc 3 events at GOES 2, since signals in the Pc 3 band in the magnetosphere are coherent over at least 20° of longitude (HUGHES *et al.*, 1978). Figure 3 shows the simultaneous observation of Pc 3 magnetic pulsations in space at GOES 2 ($L=6.6$) and at low latitude, SGC ($L=1.8$) which is located $\sim 11°$ west of GOES 2's longitude. GOES 2 and SGC located in local noon sector during 2100–2140 UT on February 2, 1981. Although it is difficult to correlate each wave peak in space and on the ground, simultaneous Pc 3 activity with a period of about 25 s is clearly seen at 2110 and 2120 UT in the GOES 2 *HP*-magnetogram and in the SGC *H*-magnetogram. The transverse pulsation with a period of about 110 s in the GOES 2 *HE*-magnetogram cannot be identified in the SGC magnetograms, because of the localized nature of the Alfvénic perturbation outside the plasmapause. In order to clarify the occurrence probability of Pc 3's having a similar period both inside and outside the plasmapause, the dominant periods are determined in each 20 min time interval of the magnetic data in the interval from January 27 to February 16, 1981. The Pc 3 events were counted if the dominant periods in the spectra of the *HP*-magnetogram at GOES 2 and the *H*-magnetogram at SGC were similar to each other, and the differences of the periods were within $\pm 10\%$. The shadowed area in Fig. 4 shows the frequency of occurrence of the compressional

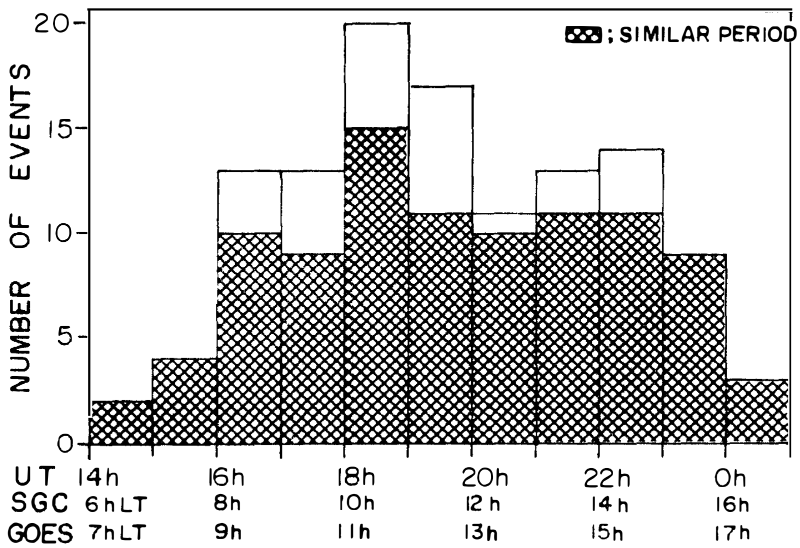

Fig. 4. Local time dependence of the relation of compressional Pc 3 pulsations observed at GOES 2 to low-latitude Pc 3's at SGC. Shadowed area indicates the frequency of occurrence of the compressional Pc 3 pulsations at GOES 2 having a similar period to the low-latitude Pc 3's at SGC during January 28–February 12, 1981.

Pc 3 magnetic pulsations at GOES 2 having a similar period to the low-latitude Pc 3 pulsations at SGC, where the amplitude of selected Pc 3 events at SGC is larger than 0.1 nT during January 27–February 16, 1981. It is found that some 70 percent of the compressional Pc 3 pulsations at GOES 2 have periods similar to the low-latitude Pc 3's observed at SGC, an L shell separation of as much as $\delta L=5$. These compressional Pc 3 pulsations observed at GOES 2 can propagate into the inner plasmasphere, and can couple with trapped oscillations and/or fundamental and higher-harmonic standing waves of local field lines in the plasmasphere. We believe that the compressional Pc 3 magnetic pulsations outside the plasmapause is one candidate for the source of the low-latitude Pc 3 pulsations. In the next section we then discuss theoretically how this can be deduced from the characteristic frequency of HM waves in the daytime magnetosphere.

3. Characteristic Frequencies of HM Waves in the Geomagnetosphere

We now turn to a consideration of characteristic frequencies of HM waves to explain the relation among Pc 3 magnetic pulsations observed in the outer magnetosphere, near the plasmapause and inside the plasmasphere. The linear resonance theory of daytime Pc 3–5 magnetic pulsations has been considered to be based on an idea of a steady state resonance coupling between a shear Alfvén wave at a local field line in the magnetosphere and an evanescent compressional wave (Real $(k_\perp^2)=(k_\perp^{real})^2-(k_\perp^{Imag})^2 \lesssim 0$), *e.g.*, a monochromatic surface wave excited at the magnetopause

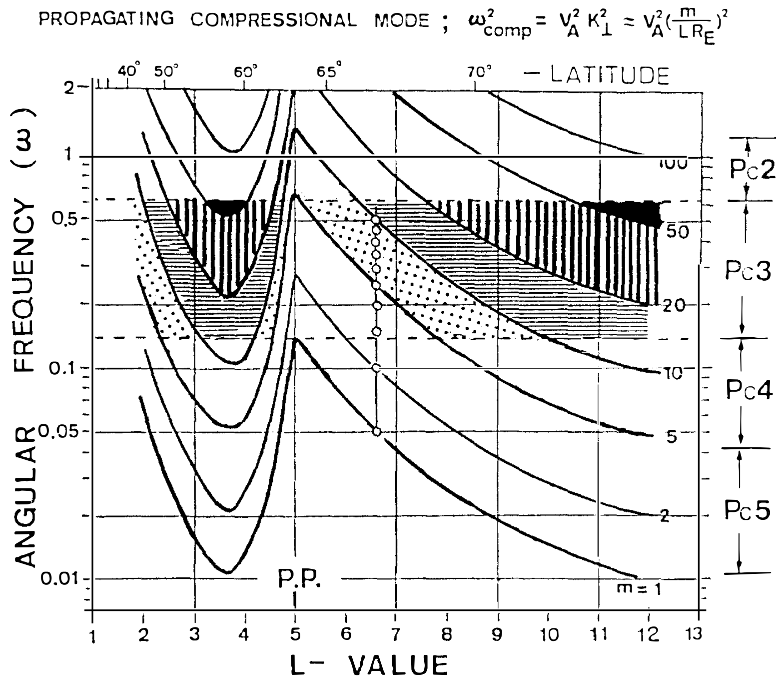

Fig. 5. The characteristic frequencies of fast magnetosonic waves in the magnetosphere are represented as functions of L-value and azimuthal wave number (m) for the plasma density and ambient magnetic field model as shown in Fig. 6.

(TAMAO, 1965; SOUTHWOOD, 1974; CHEN and HASEGAWA, 1974a). This idea of the evanescent compressional wave at the magnetopause as a source of the magnetic pulsation in the magnetosphere provides powerful support only for dawn-side Pc 4–5 pulsations (SINGER and KIVELSON, 1979; KOKUBUN, 1980; YUMOTO *et al.*, 1983b). However, compressional waves in the Pc 3 frequency range at the magnetopasue are expected to have the characteristic of a propagating mode, *i.e.*, (Real $(k_\perp^2)>$ Real $(k_\parallel^2)$) as shown in Fig. 5. Angular frequencies of the fast magnetosonic waves are illustrated as functions of L-value and azimuthal wave number (m) in the geomagnetosphere. The frequency of the propagating compressional wave with a larger azimuthal wave number is assumed to be,

$$\omega_{\mathrm{comp}}^2 = V_A^2(k_\parallel^2 + k_\perp^2) \sim V_A^2 k_\perp^2 \sim V_A^2 \frac{m^2}{(LR_E)^2}, \tag{1}$$

where ω_{comp}, $k_\parallel$ and $k_\perp$ of the compressional wave excited outside the magnetosphere stand for an angular frequency, and mean wave numbers parallel and normal to the ambient magnetic field. Although a radial wave number of isotropic compressional wave must be comparable to the order of the azimuthal wave number, the radial number is neglected in this study for simplification. The plasma model of the Alfvén velocity ($V_A^2 = B_0^2/\mu_0\rho_m$) in the daytime magnetosphere is illustrated in Fig. 6 (*cf.* YUMOTO and SAITO, 1982; YUMOTO *et al.*, 1983a). The azimuthal wave number (m) of the compressional waves in the Pc 3 frequency range is theoretically predicted to be 3–10 at synchronous orbit (L=6.6) as shown in Fig. 5. This prediction is in agreement with the observations of azimuthal wave number by multi-satellite measurements at synchronous orbit (HUGHES *et al.*, 1978).

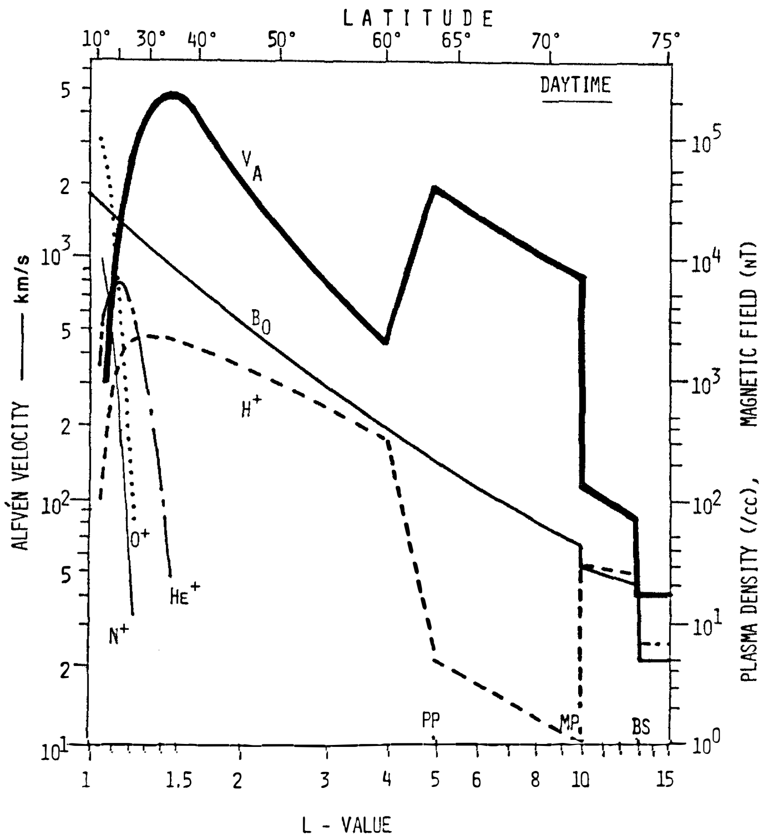

Fig. 6. Plasma density and geomagnetic field model in the daytime. The Alfvén velocity ($V_A = B_0/(\mu_0\rho_m)^{1/2}$) is represented as a function of L-value. Thick and thin solid lines express the Alfvén velocity (V_A) and the ambient geomagnetic field near the daytime magnetic equator, respectively. Other lines indicate the density of heavy ions in the magnetosphere.

Pc 3 magnetic pulsations in the outer magnetosphere are considered to be coupled oscillations between higher "harmonic" standing waves and compressional Pc 3 waves which have a $\boldsymbol{k}$ vector normal to the ambient magnetic field. The linear coupled oscillations can occur only when the resulting dispersion laws satisfy the following equation,

$$(\omega_{\mathrm{comp}}^2-\omega_{\mathrm{eigen}}^2)=[V_A^2(k_{\parallel}^2+k_{\perp}^2)-(2\pi/T_{\mathrm{eigen}}^n)^2]=0\,, \qquad (2)$$

where T_{eigen}^n is a n-th "harmonic" eigen-period of the standing resonance oscillation of a local field line in the magnetosphere. Figure 7 illustrates the higher "harmonic"

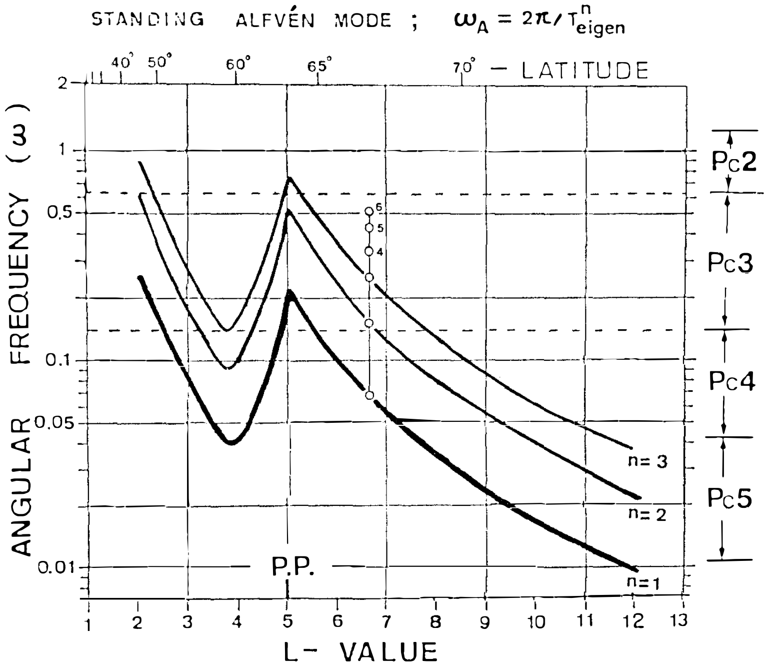

Fig. 7. The characteristic frequency of eigen-oscillations of toroidal mode against L-value in the dipolar magnetic field for the gyrofrequency plasma density model (cf. YUMOTO et al., 1983a). Thick line of n=1 stands for the fundamental eigen-oscillation of a local field line.

eigen-frequencies of the guided toroidal mode against L-value for the gyrofrequency plasma model in the dayside magnetosphere, that were numerically obtained by YUMOTO *et al.* (1983a). The fundamental eigen-frequency of standing resonance oscillations at $L=6.6$ is theoretically expected to be $\lesssim 10$ mHz (CUMMINGS *et al.*, 1969; YUMOTO *et al.*, 1983a), thus the integer (n) of higher "harmonic" modes has to be ≥ 2 for the Pc 3 frequency range in the outer magnetosphere. TAKAHASHI and MCPHERRON (1982) recently demonstrated that at least 10–30% of Pc 3 pulsations at synchronous orbit can be statistically classified as "harmonic" events consisting of many discrete "harmonic" frequencies. A sequence of frequency ratios of toroidal oscillations, which is obtained by normalizing the higher mode frequencies with the fundamental mode frequency of the standing wave as shown in Fig. 7, is represented as a function of the mode number for the numerical solution and the time of flight approximation in Fig. 8 (YUMOTO *et al.*, 1983a). The fact that the higher frequencies ω_2, ω_3, etc., of the standing wave on a local field line given by means of the time of

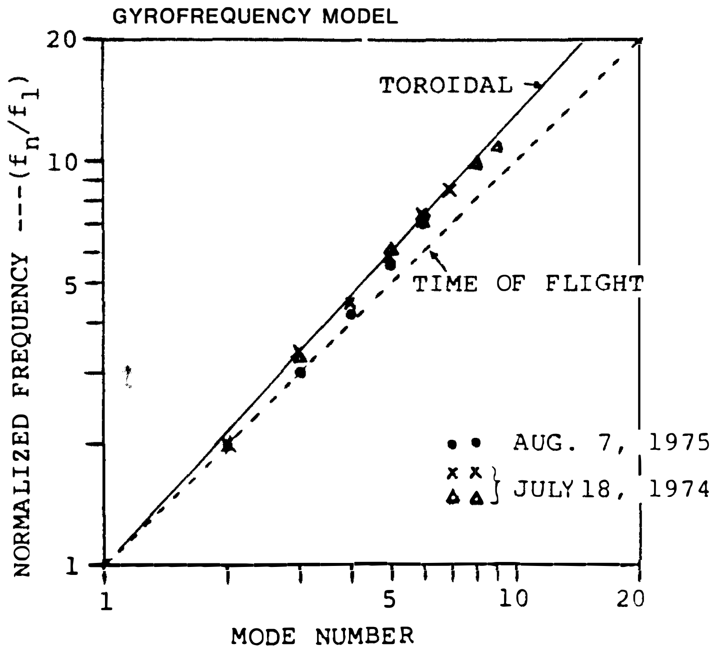

Fig. 8. Sequences of frequency ratios of the toroidal eigen-oscillations at L=6.6 vs. mode numbers. Solid and broken lines show the frequency ratio of toroidal eigen-oscillations for the numerical solution and time of flight approximation, respectively. Plots represent the normalized frequency of "harmonic events" in the Pc 3 frequency range obtained by TAKAHASHI and MCPHERRON (1982).

flight method (WKB approximation) consist of a sequence of harmonics of the lowest mode frequency ω_1 is a result of assumption that the field line is equivalently uniform and flexible. The sequence of frequency ratios of the fully developed toroidal wave indicates the slope ~1.3, *i.e.*, the eigen-frequencies of a nonuniform field line such as a dipolar magnetic field line do not form a sequence of harmonics of the fundamental. The sequence of frequency ratios of the second mode ω_2 of Pc 3 magnetic pulsations observed at synchronous orbit (*cf.* Figs. 3 and 5 of TAKAHASHI and MCPHERRON, 1982) is also replotted in Fig. 8. The observational sequence of the frequencies in the Pc 3 range at ATS 6 (L=6.6) is found to be nearly consistent with the slope of the toroidal standing wave in the dipolar background field with the gyrofrequency plasma model. Therefore, the approximations of dipolar ambient field and the gyrofrequency plasma density are good ones near synchronous orbit. Although the higher harmonic waves were not confirmed in this paper, we believe that magnetic pulsations in the Pc 3 range outside the plasmasphere consist of compressional waves and higher "harmonic" standing waves. These higher "harmonic" standing waves are radially localized and propagate into only the high-latitude ionosphere. The compressional Pc 3 waves can propagate across the ambient field into the plasmasphere and can couple with surface waves at the plasmapause, trapped oscillations in the plasmasphere, and/or eigen-oscillations of local field lines at low latitudes.

Transverse magnetic pulsations in the Pc 3 frequency range near the plasmapause are theoretically expected to consist of the collective eigen-mode of surface waves at the plasmapause (FUKUNISHI and LANZEROTTI, 1974a, b) and the standing resonance oscillation in the plasmatrough (ORR, 1973; HANSON *et al.*, 1979). The frequency of the surface eigen-mode is given approximately by

$$\omega_{CE} \sim \sqrt{2}\, k_{\parallel} V_A^{II}, \tag{3}$$

where V_A^{II} is the Alfvén velocity just inside the plasmapause (CHEN and HASEGAWA, 1974b). The value of $k_{\parallel}$ is decided by the length of the local field line l, and $k_{\parallel} = n\pi/l$ with $n \gtrsim 1$. If $V_A^{II} = 800$ km/s at $L=4$, the frequency of fundamental collective mode is ~ 10 mHz as shown in Fig. 9. Therefore, the excited Pc 3 pulsation at the

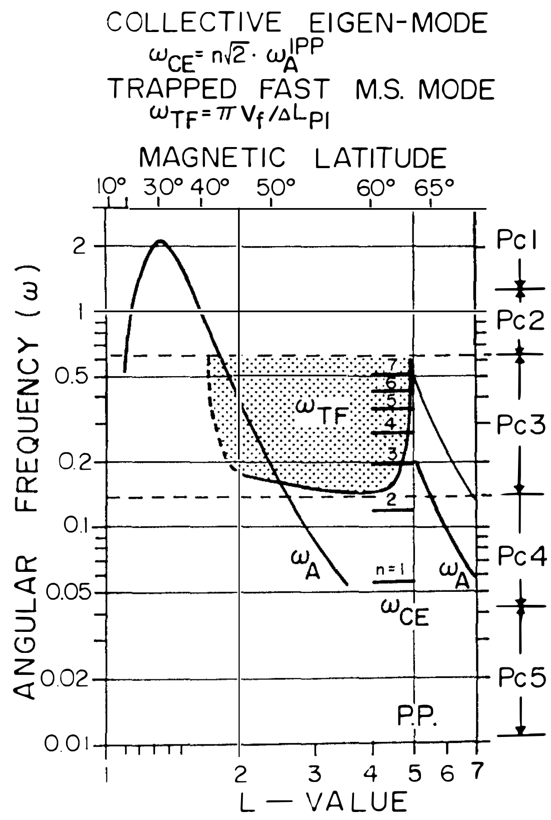

Fig. 9. Characteristic frequencies of HM waves in the plasmasphere. The frequencies ω_{CE}, ω_{TF} and ω_A represent angular frequencies of the collective eigen-oscillation, i.e., surface waves at the plasmapause, the trapped oscillation of the fast magnetosonic waves in the plasmasphere ($L=1.7 \sim L_{PP}$) and the fundamental standing eigen-oscillation of a local field line at very low latitudes ($L=1.1$ and $1.7 \sim 2.6$), respectively.

plasmapause based on the linear resonance theory is expected to be a higher harmonic of the collective eigen-mode of the surface wave. Propagating compressional waves, which have a larger normal wave number and a finite bandwidth in the Pc 3 frequency range in the outer magnetosphere, can couple with the fundamental collective eigen-oscillation at the plasmapause by means of the nonlinear resonance (YUMOTO and SAITO, 1982). The condition of the nonlinear resonance is expressed by;

$$\omega_{comp} = \omega_r + \omega_2^{fs}, \tag{4}$$

where ω_{comp}, ω_2^{fs} and ω_r are the frequencies of the propagating compressional wave in the outer magnetosphere, one component of HM-noise near the plasmapause (or a trapped oscillation of fast magnetosonic waves in the plasmasphere) and the collective eigen-oscillation (ω_{CE}) (or a standing oscillation of a local field line in the plasmasphere ($2\pi/T_{eigen}$)), respectively.

Inside the plasmapause, frequencies in the Pc 3 range are associated mainly with a fundamental standing wave at very low latitude ($L=1.1$ and 1.7–2.6), a higher-harmonic standing wave at $L=2.0\sim L_{PP}$, and a trapped oscillation of fast magnetosonic wave in the trough between two peaks of the Alfvén velocity in the inner magnetosphere ($L=1.7\sim L_{PP}$) as illustrated in Fig. 9. The period of the trapped oscillation in the plasmasphere (DOOBOV and MAINSTONE, 1973; TAMAO, 1978) is obtained approximately by $T_{trapped} \lesssim (2\Delta L/V_{g\perp})$

$$\sim 2\Delta L[V_A^2(k_{\parallel}^2+k_{\perp}^2)/k_{\perp}^2]^{-1/2} \sim 2\Delta L/V_A\,, \tag{5}$$

where ΔL is the characteristic length between two peaks of the Alfvén velocity and $V_{g\perp}$ stands for the group velocity of fast magnetosonic wave normal to the ambient magnetic field in the plasmasphere as shown in Fig. 5. If the $\Delta L \fallingdotseq L_{PP}-1.7 \approx 2.5\ R_E$ and $V_{g\perp}\sim V_A\sim 800$ km/s, the period of the trapped oscillation becomes $\lesssim 40$ s. The eigen-period of a local field line at very low latitude is expected to be ~ 20 s for an equatorial cold hydrogen plasma density $n_i\sim 2000\ \text{cm}^{-3}$ at $L\sim 2$ (ORR and MATTHEW, 1971; Fig. 9). It is difficult to understand how evanescent waves in the Pc 3 frequency range generated at the magnetopause could have sufficient amplitude and resonantly excite a standing wave of a local field line at very low latitudes, *i.e.*, so preferentially deep in the magnetosphere. The propagating compressional waves in the Pc 3 frequency range can penetrate into the plasmasphere and excite the trapped oscillation ($L=1.7\sim L_{PP}$), the fundamental ($L=1.1$ and 1.7–2.6) and higher-harmonic ($L=2.0\sim L_{PP}$) oscillations in the plasmasphere. However, further observational research is needed to examine these propagation and excitation mechanisms of the low-latitude Pc 3 magnetic pulsations and to clarify whether the observed low-latitude Pc 3 pulsations were just the propagating compressional Pc 3 waves originating at the outer magnetosphere or the coupled resonance oscillations between the propagating compressional waves and the trapped fast magnetosonic wave and/or the fundamental and higher-harmonic eigen-oscillations of a local field line in the plasmasphere.

In this section, it is theoretically confirmed that daytime Pc 3 magnetic pulsations at low latitudes are deeply associated with the propagating compressional modes in the outer magnetosphere. The relationships between the Pc 3 pulsations at various stages, *i.e.*, the solar wind, the bow shock, the magnetosheath, the magnetopause, the magnetosphere, the plasmapause, the plasmasphere, the ionosphere, and the earth surface, are insufficiently yet clarified. Future researches for multiple ground-satellite correlations and wave characteristics of Pc 3's at the various stages are needed to examine the excitation and propagation mechanisms of Pc 3 magnetic pulsations from outside the magnetosphere to very low latitude.

4. Summary and Conclusion

In order to examine whether there is a viable source of low-latitude Pc 3 pulsations in the outer magnetosphere, GOES 2 magnetic data have been analyzed in this paper. The wave characteristics of magnetic pulsations at synchronous orbit ($L=6.67$) were clarified and ground-satellite correlations were discussed by comparing the dominant frequency of magnetic pulsations at synchronous orbit with that of low-latitude Pc 3's observed at San Gabriel Canyon, which is located $\sim 11°$ west of GOES 2's longitude at $L \sim 1.8$. We can summarize the major result of the observations and analyses as follows;

(1) Compressional, radially transverse and azimuthally transverse modes of magnetic pulsations in a wide frequency range exist simultaneously in the outer magnetosphere and dominant periods of the various modes are different from one another as shown in Fig. 1.

(2) The compressional and the transverse modes of daytime magnetic pulsations at synchronous orbit are statistically dominant in the Pc 3 and in the Pc 4 frequency ranges, respectively (*cf.* Fig. 2).

(3) Some 70 percent of the compressional Pc 3 pulsations at GOES 2 have a similar period to the low-latitude Pc 3's observed at SGC (Fig. 4).

On the other hand, characteristic frequencies of HM waves in the geomagnetosphere as shown in Fig. 10 were theoretically discussed to show clearly the excitation and propagation mechanisms of daytime Pc 3 magnetic pulsations in the magnetosphere; these are summarized as follows;

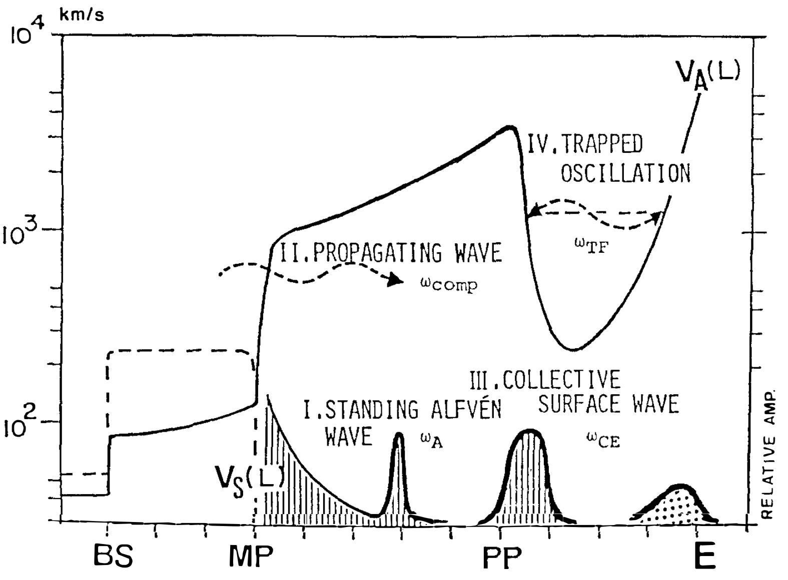

Fig. 10. Schematic presentation of HM-waves in the Pc 3 frequency range in the geomagnetosphere. A standing Alfvén wave (ω_A) outside the plasmapause (PP) is excited by an evanescent compressional wave at the magnetopause (MP) or a propagating compressional wave (ω_{comp}) outside the magnetosphere. The propagating compressional wave (ω_{comp}) in the Pc 3 frequency range can couple with (i) a collective surface wave (ω_{CE}) at the plasmapause ($L=L_{PP}$), (ii) a trapped oscillation (ω_{TF}) at $L=1.7\sim L_{PP}$, (iii) a higher-harmonic ($L=2.0\sim L_{PP}$) and (iv) a fundamental ($L=1.1$ and 1.7–2.6) standing eigen-oscillation (ω_A) of a local field line in the plasmasphere. $V_A(L)$ indicates a model of the Alfvén velocity ($B_0/(\mu_0\rho_m)^{1/2}$) in the daytime magnetosphere.

(4) Daytime magnetic pulsations in the Pc 3 frequency range in the outer ($L \gtrsim 6$) magnetosphere consist of the fast magnetosonic wave with a larger azimuthal wave number ($m \geq 3$–10) and the higher "harmonic" ($n \gtrsim 2$) standing wave of a local field line. The Alfvénic modes of the higher "harmonic" standing waves can propagate only into the high-latitude ionosphere. The compressional Pc 3 waves can propagate across the ambient magnetic field into the plasmasphere.

(5) Transverse magnetic pulsations in the Pc 3 frequency range, which must be excited mainly by the compressional Pc 3 waves near the plasmapause, are either the higher "harmonic" mode of collective eigen-oscillations, *i.e.*, surface waves at the plasmapause, or the standing waves of a local field line just outside the plasmapause, *i.e.*, in the plasmatrough.

(6) In the plasmasphere, the compressional Pc 3 waves from outside the plasmapause can propagate into the low-latitude ionosphere and can couple with any of (i) a trapped oscillation of the fast magnetosonic wave in the trough between two peaks of the Alfvén velocity ($L=1.7 \sim L_{PP}$), (ii) a higher-harmonic standing oscillation of a local field line at the mid-latitude ($L=2.0 \sim L_{PP}$) and (iii) a fundamental standing eigen-oscillation at very low latitudes ($L=1.1$ and 1.7–2.6).

Ground magnetometer arrays are recently well suited to the investigation of the role of the plasmapause on the Pc 3 magnetic pulsations during and since the International Magnetospheric Study. The work of the Bell Laboratory group (FUKUNISHI and LANZEROTTI, 1974a, b; LANZEROTTI *et al.*, 1974; LANZEROTTI and FUKUNISHI, 1975) had detected polarization reversals at the inferred position of the plasmapause. HANSON *et al.* (1979) further found that there are two well-defined maxima in the contour map of the H-amplitude observed at the extensive latitudinal array of I.G.S. magnetometer (GREEN, 1981). The ellipticity contour of the Pc 3 pulsation was also demonstrated in the figure of HANSON *et al.* (1979). They suggested that the latitudinally higher maximum seemed to be a resonance with polarization reversal at the density gradient of the plasmapause, and the lower one to be a field line resonance with no polarization reversal inside the plasmasphere. However, it should be mentioned that in their works the plasmapause position based on the empirical model of ORR and WEBB (1975) is used only in the absence of a satellite-based density measurement. There are two HM waves in the Pc 3 frequency range near the plasmapause, *i.e.*, the higher harmonic wave of the collective eigen-oscillation at the plasmapause and the fundamental standing eigen-oscillation of a local field line just outside the plasmapause *i.e.*, in the plasmatrough as shown in Fig. 9. Therefore, more direct measurement of the plasmapause position from whistler observations and satellite observations is needed to obtain more useful information concerning the location of the resonance region of Pc 3 magnetic pulsations. The lower maximum of the Pc 3 pulsations with no obvious sense-of-polarization reversal at $\sim 53°$ latitude ($L \sim 2.8$) may be the trapped oscillation of the fast magnetosonic wave in the trough of Alfvén velocity in the plasmasphere.

JACOBS and WATANABE (1962) pointed out the possibility that a filtering action of the region between the bottom of the ionosphere and the layer of maximum Alfvén velocity around 2000 km explains not only 'pearl' type oscillations, mostly nighttime phenomena, but also daytime low-latitude Pc pulsations in the periods range 20–30 s caused by the secondarily emitted waves propagating from high latitudes in the region. GREIFINGER and GREIFINGER (1965) considered the case of a plane wave propagating in the vertical direction in the presence of a uniform magnetic field which was also in the vertical direction. The model was thus strictly applicable only to the polar and auroral regions. FIELD and GREIFINGER (1965) extended their investigation of the transmission in the Pc 1–4 frequency range. FIELD and GREIFINGER (1966) further extended their work to the case when the geomagnetic field was horizontal rather than vertical, *i.e.*, they considered an equatorial propagation. The daytime composite transmission coefficient of the HM waves falls off very rapidly with increasing frequency and exhibits a series of rather small resonances, although the nighttime equatorial coefficient has many of the strong resonance characteristics as the polar ones, indicating the nocturnal appearance of Pc 1, Pi 2 and/or Pc 4 classes of low- and mid-latitude geomagnetic pulsations. Further theoretical analysis for the transmission mechanism of daytime HM waves into the equator in the horizontal geomagnetic field, *e.g.*, a combined theory of propagation mechanisms proposed by JACOBS and WATANABE (1962), FIELD and GREIFINGER (1966), and in the preceding section, is needed to explain the existence of low-latitude Pc 3-type magnetic pulsations in a subtropical region (SAITO *et al.*, 1983).

SEN (1968a, b) suggested that the effect of the long inhomogeneous transmission path from the magnetospheric boundary to the ionosphere was of profound importance in determing the spectrum of magnetic pulsations. HM surface waves generated by a Kelvin-Helmholtz instability were considered to leave the boundary along lines of forces of the geomagnetic field and travel towards the surface of the earth as magnetic pulsations. Although he showed that amplitude spectrum of magnetic pulsation's signals observed on the ground was essentially determined by the resonances of the transmission path in the case of the simple plasma model for the outer magnetosphere, further comparisons between observed spectral peaks of magnetic pulsations and numerical predictions of the transmission resonances for more realistic plasma model of the magnetosphere are needed to reexamine the mechanism how incident waves having no sharp spectrum from outer space could be filtered into geomagnetic pulsations within the Pc 2, Pc 3, Pc 4 and Pc 5 frequency bandwidths on the ground. A filtering action in the magnetospheric boundary layer is discussed for daytime Pc 3–5 pulsations in the outer magnetosphere (YUMOTO, 1984).

Although future researches are needed to examine the wave and propagation characteristics of daytime magnetic pulsations by multi-satellite and ground-satellite observations from the outer magnetosphere to very low latitudes on the ground, we believe that the compressional Pc 3 magnetic pulsation observed at GOES 2, which can propagate across the ambient geomagnetic field to low latitudes, is one of the most possible source of low-latitude Pc 3 magnetic pulsations.

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