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Generation and propagation mechanisms of low-latitude magnetic pulsations – A review

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Contents

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1. Introduction

It is more than thirty years since J.W. Dungey first suggested that sinusoidal oscillations in the earth's magnetic field, recorded almost a hundred years before by B. Stewart and known as geomagnetic pulsations, were due to hydromagnetic waves in the magnetosphere. In recent years there has been an amazing increase in both the quantity and quality of data due to new techniques of measurement such as the availability of extensive magnetometer chains, multisatellite observations, and auroral radars, in addition to the many advances in our theoretical understanding of the phenomena (see review of Hughes, 1983).

Magnetic pulsations can be basically classified into two groups. One is "exogenic" pulsations which are continuously driven by the solar wind. The other is "endogenic" pulsations which are excited mainly by transient and abrupt changes of the ambient magnetized plasma and/or the free energy stored in the earth's magnetosphere. The present review deals mainly with low-latitude Pc 3 (T=10–45 s) and Pi 2 (40–150 s) magnetic pulsations, which can be categorized as "exogenic" and "endogenic" pulsations, respectively. A significant part of the "exogenic" Pc 3 pulsations observed in daytime is in some way a function of the state of the solar wind (cf. Verö, 1985). It has been recently demonstrated that daytime Pc 3 magnetic pulsations assume an important role in the transmissions of the solar wind energy into the inner magnetosphere, which is of vital importance in understanding the physics of important aspects of the solar wind-magnetosphere interaction (Wolfe et al., 1985; Yumoto et al., 1985a). On the other hand, "endogenic" Pi 2 pulsations have been considered as transient hydromagnetic signals associated with substorm expansion onsets or intensifications (see Baumjohann and Glassmeir, 1984). Therefore, Pi 2 magnetic pulsations are generally believed to play an important role in the dynamic coupling of the magnetosphere and the ionosphere during substorm expansion onset (e.g., Nishida, 1979; Lysak and Dum, 1983; Sun and Kan, 1985). Undoubtedly it seems worthwhile now to review both our knowledge and our ignorance and to clarify how low-latitude Pc 3 and Pi 2 magnetic pulsations assume important roles in the dayside solar-terrestrial relationships and in the magnetosphere-ionosphere couplings, respectively.

In Sect. 2, we will review the generation and propagation mechanisms of hydromagnetic energies in the Pc 3 frequency range in the solar wind into the inner magnetosphere ($L \sim 1.5$). Wave characteristics of Pc 3 pulsation at $L \lesssim 3.0$ will be theoretically and observationally investigated. The generation mechanism of very low latitude Pc 2–3 ($\Phi < 22°$) will be also theoretically discussed. In Sect. 3, selected wave characteristics of Pi 2 pulsations will be summarized with an emphasis on the unresolved generation and propagation mechanisms of low-latitude Pi 2. After theoretical models of Pi 2 pulsations have been reviewed, we propose a possible Pi 2 model. In the final section, conclusions and remaining future studies on the generation and propagation mechanisms of low-latitude magnetic pulsations will be summarized.

2. Low-latitude Pc 3 magnetic pulsations

2.1 Introduction

Low-latitude Pc 3 magnetic pulsations have been recently studied by many scientists (Verö, 1980, 1981; Lanzerotti

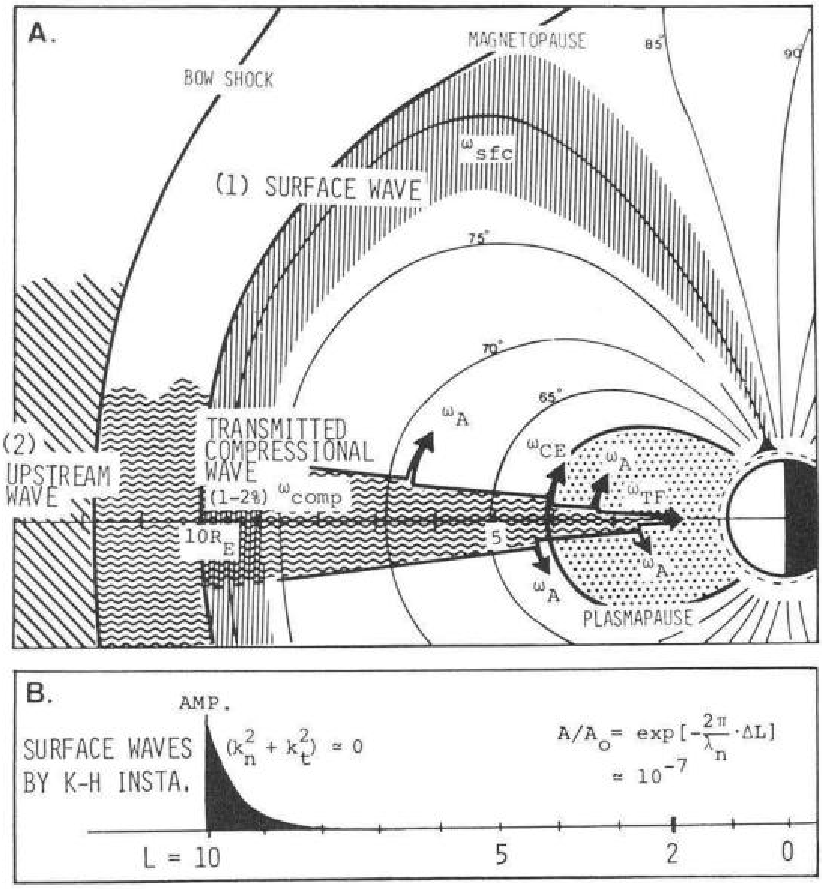

Fig. 1 A and B. Two possible generation mechanisms for daytime Pc 3 (after Yumoto et al., 1985a). **A** Surface waves in the Pc 3 range excited by the Kelvin-Helmholtz-type instabilities in the dayside high-latitude boundary layer can transmit only into the high-latitude ionosphere. Magnetic upstream waves in the earth's foreshock can propagate into the magnetosphere, can couple with various HM oscillations (ω_A^n, ω_{CE}, ω_{TF}) in the inner magnetosphere, and then can be a source of low-latitude Pc 3 magnetic pulsations. **B** Damping rate (A/A_o) of typical Pc 3 surface waves in the radial direction. The Pc 3 amplitude at $L = 2.0$ is seven orders of magnitude below that at the magnetopause for wavelength $\lambda \sim 3\ R_E$

et al., 1981; Kunaratnam, 1981; Yumoto and Saito, 1982, 1983; Green et al., 1983; Russell et al., 1983; Saito et al., 1984; Sutcliffe and Poole, 1984; Yumoto et al., 1984, 1985a; Fraser and Ansari, 1985; Odera and Stuart, 1985; Saka and Kim, 1985). It is generally accepted that there are two candidates of main exogenic sources for daytime Pc 3–4 pulsations as shown in Fig. 1a. One is surface waves excited by the shear flow (Kelvin-Helmholtz-type) instability driven by the solar wind at the dayside high-latitude magnetospheric boundary (Miura, 1984; Yumoto, 1984; Yumoto et al., 1985a). The other is the bow-shock-associated wave phenomena associated with particle reflected and/or accelerated by the bow shock (Fairfield, 1969; Russell et al., 1971; Greenstadt, 1976; Russell and Hoppe, 1983; Yumoto et al., 1984).

However, the existence of Pc 3 pulsations at very low latitudes on the ground is difficult to explain if they are related to the surface waves at the dayside high-latitude magnetopause because of the high damping rate of the evanescent wave in the Pc 3 frequency range in the radial direction as shown in Fig. 1b (cf. Lanzerotti et al., 1981; Yumoto et al., 1984). The damping rate $[A/A_o]$ of typical Pc 3 surface waves in the radial direction produces an amplitude reduction of seven orders of magnitude from the magnetopause to $L = 2.0$ for a typical Pc 3 wavelength of $\lambda = 3\ R_E$. The Pc 3 surface waves can only penetrate into the high-latitude ionosphere and then could be observed as high-latitude Pc 3 magnetic pulsations (see Sect. 2.4). Lanzerotti et al. (1981) proposed a possible way to obtain low-latitude waves without excessive damping for excitation by disturbances produced in the magnetospheric cusp, and suggested that these cusp disturbances would propagate to lower latitudes via the ionosphere. Some authors had also studied the transmission process of HM waves in the ionosphere from high latitudes to the equator, as reviewed in Sect. 3.4. However, it has not yet been theoretically examined how low-latitude Pc 3 standing oscillations observed at $L \sim 1.5$ (see Sect. 2.7) could be excited by the transmitted Pc 3 disturbance in the ionosphere. Moreover, morphological relationships between high-latitude Pc 3 and low-latitude Pc 3 are still not conclusively clarified. Further theoretical and observational studies are needed to investigate quantitatively the transmission of Pc 3 pulsations in the ionosphere.

On the other hand, studies of the solar-wind-controlled mid- and low-latitude Pc 3–4 pulsations have been highlighted (see Greenstadt et al., 1980; Wolfe et al., 1980; Odera, 1986). The fact that magnetosonic upstream waves with 15–100 mHz range, excited by the reflected ion beams in the earth's foreshock (cf. Tsurutani and Rodriguez, 1981; Russell and Hoppe, 1983), transmit into the magnetosphere without significant changes in spectra recently appears to be accepted (Yumoto and Saito, 1983; Greenstadt et al., 1983; Yumoto et al., 1984; Yumoto, 1985). The transmitted compressional Pc 3–4 waves are believed to be a main source of low-latitude Pc 3–4 pulsations (Wolfe et al., 1985; Yumoto et al., 1985a).

The purpose of this section is to review the generation and propagation mechanisms of Pc 3 magnetic pulsations observed at low latitudes ($L \lesssim 3.0$). The generation mechanism of upstream waves in the Pc 3–4 frequency range in the earth's foreshock will be summarized in Sect. 2.2. Trans-

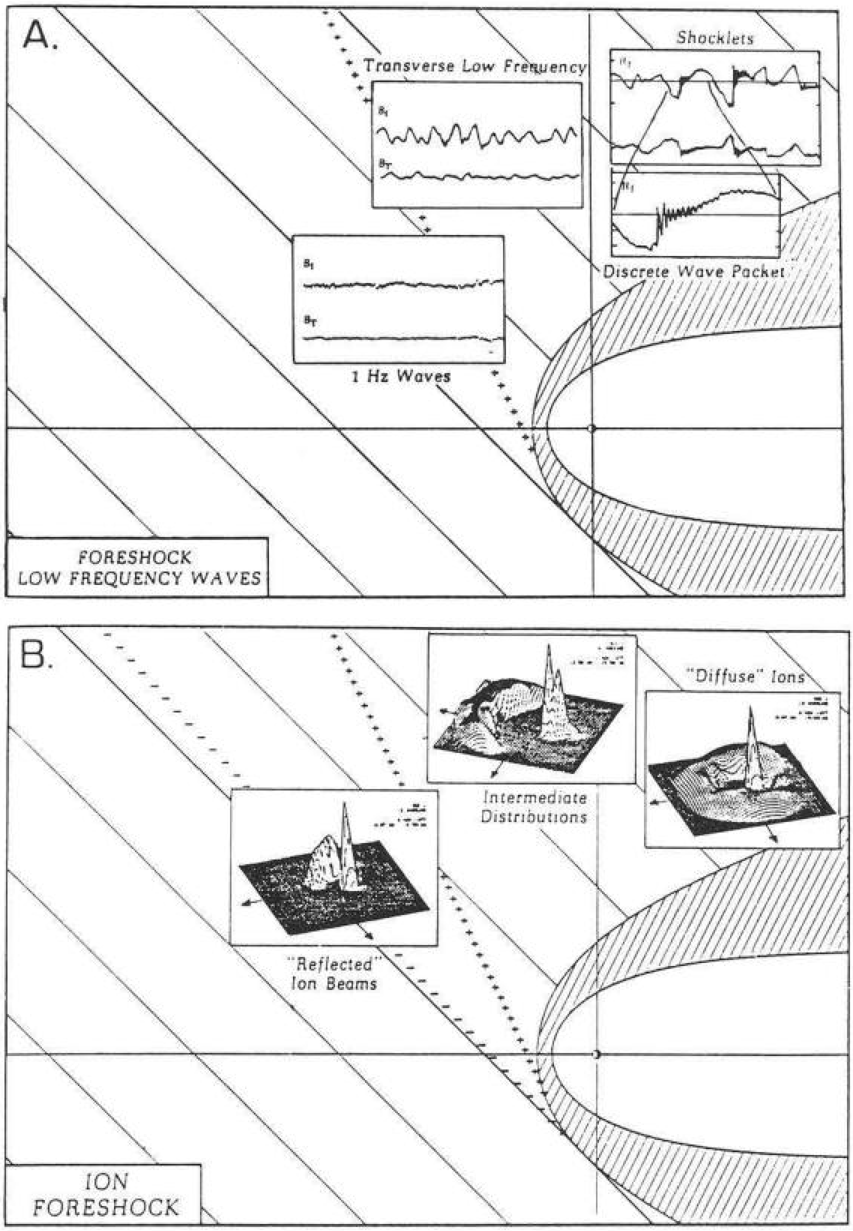

Fig. 2A and B. Upstream waves and particles (after Russell and Hoppe, 1983). **A** Low frequency upstream waves, i.e., the transverse low-frequency and shocklet waves, are associated with ion distributions of the earth's foreshock. The 1-Hz waves are associated with electron anisotropies and are observed both upstream and downstream of the ion foreshock boundary. **B** Ion distributions of the earth's foreshock. The high narrow peak in each distribution is the solar wind. The foreshock ions appear as a narrow "reflected" beam, as the kidney-bean-shaped intermediate ions, and the more nearly isotropic "diffuse" distributions. The upstream boundaries of foreshock electrons (−) and ions (+) are sketched

missions of the Pc 3–4 upstream waves through the bow shock and the magnetopause into the outer magnetosphere will be described in Sect. 2.3. In Sects. 2.4 and 2.5, propagation mechanisms (i.e., coupling mechanisms) of Pc 3–4 source waves from the outer to the inner magnetosphere will be discussed. Characteristic frequencies of various Pc 3–4 oscillations coupled with the source waves will be theoretically summarized in Sect. 2.6. Wave characteristics of low-latitude Pc 3 pulsations observed at conjugate stations will be demonstrated in Sect. 2.7. Finally, a generation mechanism of Pc 2–3 observed at very low latitudes ($L <$ 1.2) and unresolved problems will be discussed in Sect. 2.8.

2.2 Upstream waves as a source of low-latitude Pc 3

A major early discovery was the existence of large-amplitude low-frequency waves that fill most of the upstream region that is connected to the bow shock by the interplanetary magnetic field (IMF) (Greenstadt et al., 1968; Fairfield, 1969). The upstream waves are considered to be generated by reflected protons coming from the earth's foreshock (Fairfield, 1969; Barnes, 1970; Fredricks, 1975; Kovner et al., 1976; Gray et al., 1981; Lee, 1982; Watanabe and Terasawa, 1984; Hada et al., 1986). Using magnetic field data from the dual ISEE 1 and 2 spacecraft, Hoppe and Russell (1983) have determined the plasma rest-frame frequencies of the large-amplitude, low-frequency upstream waves as shown in Fig. 2a. The monochromatic sinusoidal waves associated with "intermediate" ion fluxes (Fig. 2b) were concluded to be magnetosonic waves with rest-frame frequency ~ 0.05–0.2 times the ion cyclotron frequency (Ω_i) and wavelength $\sim 1\ R_E$ in the earth's foreshock. They also identified these as magnetosonic right-handed mode signals from the rest-frame polarizations.

On the other hand, Gosling et al. (1978) reported the presence of two distinct and mutually exclusive populations of low-energy ions ($\lesssim 40$ KeV) in the upstream solar wind, so-called "reflected" and "diffuse" components. Paschmann et al. (1981) indicated the distinction among three types of upstream ion populations on the basis of pronounced differences in their distribution functions, i.e., "reflected" ion beam, "intermediate," and "diffuse" ion distribution (Fig. 2b). Although the low-frequency magnetosonic waves with larger amplitude were demonstrated to be associated mostly with the intermediate and diffuse ion distributions (Paschmann et al., 1980, 1981; Sentman et al., 1981; Hoppe et al., 1981; Tsurutani and Rodriguez, 1981; Russell and Hoppe, 1983), it is generally considered that instability of the reflected ion beams generates waves; the waves pitch angle scatter the beams into intermediate and diffuse distributions and then all are convected back toward the shock (Gray et al., 1981; Bavassano-Cattaneo et al., 1983; Hoppe and Russell, 1983). Recently, Hada et al. (1986) theoretically studied the relations between the ion distributions and large-amplitude upstream waves and excitations of compressional waves in the earth's foreshock in detail.

Paschmann et al. (1981) showed the large velocity variation of reflected ions from 650 km/s to 1,150 km/s in the solar wind frame, i.e., in the rest frame. If the low-frequency magnetosonic waves with $(\omega/\Omega_i)=0.05$–0.2 in the earth's foreshock (Hoppe and Russell, 1983) are assumed to be a magnetosonic right-handed wave excited by the well-established cyclotron resonance mechanism driven by narrow reflected ion beams (Stix, 1962; Kennel and Petschek, 1966), the proton resonant velocity ($V_{\|}$) in the solar wind frame can be expected to be $(V_{\|}/V_A)\ \sim 8$–20 with respect to the resonance condition (Yumoto et al., 1984). The local Alfvén velocity (V_A) in the upstream region is typically ~ 50 km/s, so that the proton resonant velocity ($V_{\|}$) exciting the magnetosonic right-handed waves with $(\omega/\Omega_i)=0.05$–0.2 in the rest frame is inferred to be 400–1,000 km/s. This inference is in agreement with the range of the observed velocities of reflected ion beams in the solar wind frame (Paschman et al., 1981). When the cone angle θ_{XB} of the IMF is small, the subsolar foreshock is occupied by complex, compressional waves. Although the relationship between the IMF magnitude and the frequencies of the complex, compressional foreshock waves have not been published, the low-frequency magnetosonic waves with large amplitude in the earth's foreshock could be associated with the magnetosonic right-handed waves excited by the anomalous Doppler-shifted ion cyclotron resonance with the narrow reflected ion beams.

2.3 Transmission of upstream waves through the bow shock and the magnetopause

Many authors have theoretically studied the transmitted magnetohydromagnetic waves in the magnetosheath resulting from the incidence of an upstream wave on the bow shock (Westphal and McKenzie, 1969; Barnes, 1970; Fairfield and Ness, 1970; McKenzie and Bornatici, 1974; Hassam, 1978; Zhuang and Russell, 1982). They tried to explain the higher level of fluctuations in the magnetosheath than in the upstream solar wind on the basis of Snell's law, i.e., the continuity of the frequency and the tangential component of the wave vector. Zhuang and Russell (1982) concluded that the fast mode of upstream waves whose incident angle is less than the critical angle ($\sim 20°$) can enter through and be amplified by the bow shock. The amplified waves are believed to account for the low-frequency turbulence-like structure observed downstream of the quasi-parallel shock (McKenzie and Westphal, 1970; McKenzie, 1970).

Using a convection pattern model of the shocked solar wind flow around the Venus obstacle, Luhmann et al. (1983) recently demonstrated that the period and polarization of ULF magnetic fluctuations observed by Pioneer Venus in the magnetosheath are similar to those observed upstream of the quasi-parallel bow shock. Russell et al. (1983) have found the L value dependence of the IMF cone angle effect, i.e., when θ_{XB} is 15° or less, the normalized rate of occurrence of daytime Pc 3–4 pulsations of $L=2.4$–4.3 is much higher near zero θ_{XB} at low latitudes than at high latitudes. The L value dependence of the IMF cone angle effect was examined quantatively by using a simple approximation to the magnetosheath flow field for a variety of angles between the IMF and shock normal, θ_{BN} as shown in Fig. 3. When $\theta_{XB}=0°$, upstream waves which are most intense near the streamline that passes through the shock at θ_{BN} of 0° are believed to propagate radially inward and be convected to the magnetopause. When θ_{XB} becomes larger, upstream waves generated away from the subsolar region of the shock have access to the magnetopause by propagating across streamlines until far downstream in the magnetosheath, but these do not seem to penetrate deeply into the magnetosphere. They concluded that the sharp dependence on θ_{XB} at low L values probably reflects the dependence of upstream wave amplitude at the nose of the shock on θ_{XB}, whereas the weaker θ_{XB} dependence at higher L values is indicative of cross streamline propagation and wave coupling over a range of a local times.

The mechanism of MHD wave transmission in the Pc 3 frequency range through the tangential discontinuity at the earth's magnetopause was theoretically demonstrated to be important for magnetosonic fast waves with a nearly normal incident angle (McKenzie, 1970; Verzariu, 1973; Wolfe and Kaufmann, 1975). The transmission coefficient averaged over a hemispherical distribution of incident fast waves was found to be 1%–2%. The daily averaged magnitude of energy flux deposited into the magnetosphere over a hemispherical distribution of waves having amplitudes of say 2–3 nT, has been estimated to be on the order 10^{22} erg. Therefore, the energy input of MHD waves can contribute significantly to the energy budget of the magnetosphere (Verzariu, 1973).

For the magnetopause of a rotational discontinuity, Kwok and Lee (1984) demonstrated that five types of incident waves (Alfvén, fast and slow magnetosonic, convected slow and entropy waves) from upstream (magnetosheath) can exist and transmissions occur over a wide range of incident angle. The fast magnetosonic wave reflected from the magnetopause at a rotational discontinuity was also suggested to contribute to the cause of magnetosheath turbulence. The integral power of the Alfvén-wave transfer was found to be proportional to the total open magnetic flux in the magnetosphere and is typically $\sim 1\%$ of the electromagnetic energy transfer rate across the open magnetopause (Lee, 1982). The numerical results for wave transmission at a rotational discontinuity indicated a strong dependence of the transmitted wave amplitudes on the B_n/B_t ratio (the normal to the tangential component of the ambient magnetic field), which can also be dependent on the solar wind velocity and the rotation angle of the magnetic field (see Figs. of Kwok and Lee, 1984). This theoretical result supports the control of the solar wind velocity on

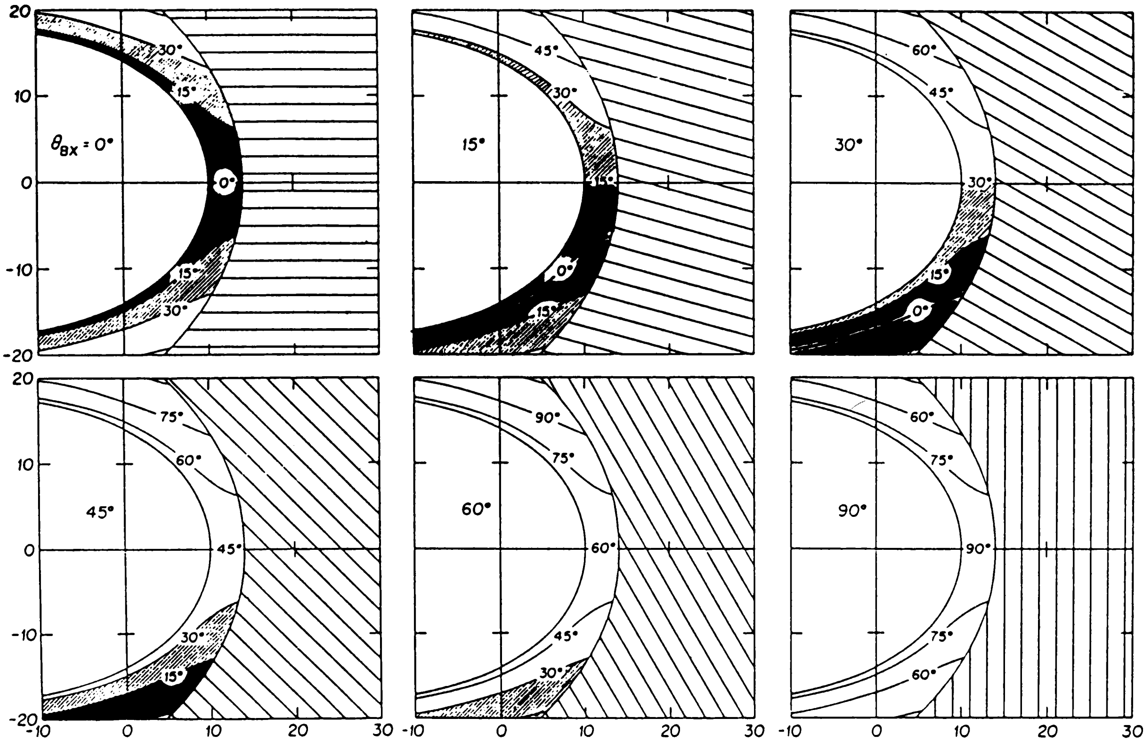

Fig. 3. Relation between the IMF cone angle (θ_{BX}) and Pc 3–4 waves in the magnetosheath (after Russell et al., 1983). Pc 3–4 waves are assumed to be generated at the shock only for the angles $\Theta_{BN} = <(\mathbf{B}_{IMF}, \mathbf{n}_{shock}) \lesssim 15°$ and then to be convected back without propagating across stream lines. Stream lines in the $B-V$ plane in the magnetosheath are labelled and shaded according to the Θ_{BN} angles at the point the streamline crosses the shock

the Pc 3–4 activity in daily averages, especially when the Kelvin-Helmholtz mechanism is expected not to be effective (Wolfe et al., 1980).

Wolfe et al. (1985) recently demonstrated that the correlation between the low-latitude geomagnetic power in the Pc 3 frequency range (15–30 s) and the interplanetary conditions is slightly better for the case of negative B_z of the IMF than for the case of the unconstrained north/south direction. This evidence is believed to suggest that power of Pc 3 source waves is transmitted more readily across an open magnetopause, i.e., across interconnected field lines, or rotational discontinuities. However, component-by-component details of the transfer process, the global picture describing where the most effective transfer takes places, and the pathways whereby broadband energy in the magnetosheath is recorded as monochromatic pulsations in the magnetosphere remain to be clarified.

2.4 Propagation mechanism of Pc 3 source waves into the deep magnetosphere

From the comparison of power spectra of magnetic field data from ISEE 1 and 2 recorded simultaneously on both sides of the magnetopause, Greenstadt et al. (1983) observationally demonstrated that the same frequencies were enhanced on the two sides of the boundary. Ratios of the magnetic power in the magnetosphere to that in the magnetosheath in the $0.01 < f < 0.1$-Hz range were found to be from about 0.001 to 0.08. Such low ratios across the magnetopause are consistent with those of transferred powers predicted theoretically by Verzariu (1973) for tangential discontinuities and by Lee (1982) for rotational discontinuities, and demonstrated observationally in single-satellite crossing by Wolfe and Kaufmann (1975). These results support the theory of external wave origin, i.e., the transfer of a small fraction of magnetosheath wave power which is possibly derived from quasi-parallel shock structure (Greenstadt, 1972; Kovner et al., 1976) and/or magnetosonic upstream waves originating in the earth's foreshock (see Sect. 2.2), across a stable magnetopause into the magnetosphere to appear as waves in the Pc 3–4 range.

On the other hand, another candidate for an exogenic source of daytime Pc 3–4 pulsations is generally believed to be surface waves excited by Kelvin-Helmholtz type instability at the dayside high-latitude magnetopause (see Yumoto, 1984). However, the existence of Pc 3 pulsations at very low latitudes is difficult to explain by the surface waves at the magnetopause because of the higher damping rate of the evanescent waves in the radial direction as shown in Fig. 1b (cf. Lanzerotti et al., 1981; Yumoto et al., 1984). The damping rate $[A/A_o = \exp(ik_n \Delta L)]$ of typical Pc 3 evanescent waves is of the order 10^{-3} for $\lambda_{\parallel} \sim (V_f/f) \sim 500$ km s^{-1}/60 mHz~ 1 R_E at the penetrating distance of $\Delta L = 1$ R_E from the magnetopause in the radial direction, where A, k_n, $\lambda_{\parallel}$, V_f, and f indicate the amplitude, wave number in the normal direction, characteristic Pc 3 wave length parallel to the magnetopause, phase velocity, and frequency of the surface waves with $k_n^2 + k^2{}_{\parallel} = k_n^2 + (2\pi/\lambda_{\parallel})^2 \sim 0$, respectively. The Kelvin-Helmholtz instabilities occurring mostly at the flank-side magnetopause (Southwood, 1968, 1979; Yumoto and Saito, 1980) are not a likely process to account for daytime Pc 3–4 pulsations observed predominantly near local noon.

Uberoi (1983) described the compressional surface wave at the magnetopause, penetrating into the inner magnetosphere by the following approximate dispersion relation:

$$w^{\text{surf}}_{\text{comp}} \sim V_{\text{A}}(k_{\perp}/\tan\theta)\,(2\rho_{\text{o}1}/\rho_{\text{o}2})^{1/2} \tag{1}$$

where $\omega^{\text{surf}}_{\text{comp}}$, V_{A}, ${}_{\perp}k$, θ, and $\rho_{\text{o}1}/\rho_{\text{o}2}$ stand for the angular frequency, Alfvén velocity, mean wave number normal to the ambient field, wave propagation angle from the ambient magnetic field ($\theta > 60°$), and ratio of plasma density in the outer magnetosphere to the magnetosheath, respectively. The compressional propagating wave (i.e., fast magnetosonic mode) was approximately expressed by $\omega_{\text{comp}} \sim V_{\text{A}}k_{\perp}$ (see Yumoto and Saito, 1983). If $k_{\perp} = (k_{\text{R}}^2 + k_{\text{A}}^2)^{1/2} \sim (m/LR_{\text{E}})$ and $\rho_{\text{o}2}/\rho_{\text{o}1} \sim 20$, azimuthal wave numbers m_{surf} of the compressional surface wave and m_{prop} of the propagating compressional wave can be expressed as follows:

$$m_{\text{surf}} \sim (\omega^{\text{surf}}_{\text{comp}}/V_{\text{A}})\, LR_{\text{E}} \tan\theta\sqrt{}10 \tag{2.1}$$

and

$$m_{\text{prop}} \sim (\omega_{\text{comp}}/V_{\text{A}})\, LR_{\text{E}}. \tag{2.2}$$

For $\omega^{\text{surf}}_{\text{comp}} \sim \omega_{\text{comp}} \sim 2\pi/T = 2\pi/20$ s, $\theta \sim 72°$, and $V_{\text{A}} \sim 1{,}500$ km/s at $L \sim 2$, we have $m_{\text{surf}} \sim 26$ and $m_{\text{prop}} \sim 3$. On the other hand, Ansari and Fraser (1985), Fraser and Ansari (1985), and Sutcliffe (1985) recently observationally demonstrated that azimuthal wave numbers of low-latitude Pc 3 are typically $\lesssim 6$ at $L \lesssim 2.0$. The low-latitude Pc 3 having smaller m $\lesssim 6$ cannot be explained by the linear resonance theory of surface waves excited by the Kelvin-Helmholtz-type instabilities at the magnetopause (Southwood, 1974; Chen and Hasegawa, 1974a; Uberoi, 1983). Low-latitude Pc 3 pulsations with m $\sim$ 3–6 are believed to couple directly with the compressional Pc 3 waves propagating in the magnetosphere (cf. Yumoto et al., 1985a; Sect. 2.5).

From the theoretical considerations and observational facts, it is concluded that a main source of low-latitude Pc 3 pulsations is the magnetosonic upstream waves, being transmitted from outside the magnetosphere and propagating across the ambient magnetic field into the inner magnetosphere.

2.5 Transmitted Pc 3 source waves in the magnetosphere

In this section, we will summarize observational evidence that wave characteristics of Pc 3 waves in the magnetosphere are related to the solar wind parameters and thus support the transmission of the magnetosonic upstream waves into the magnetosphere.

On the basis of data analysis of Pc 3 band waves at geosynchronous orbit, Arthur and McPherron (1977) first reported that no relationship was found between the interplanetary magnetic field (IMF) magnitude and the frequency of both transverse and compressional magnetic pulsations, but that there was a clear, although weak, relationship between the cone angle of the IMF and the amplitude of the pulsations. Takahashi et al. (1984) also demonstrated that pulsation events exhibiting the harmonic structure (i.e., high-harmonic standing waves) at geostationary orbit, show a weak negative correlation between pulsation frequencies and the IMF magnitude. The above results of the dependence of Pc 3 frequencies at the synchronous orbit on the IMF magnitude can be explained by considering the existence of both standing Alfvén waves with larger amplitudes on local field lines and compressional waves with smaller amplitudes propagating from outside the magnetosphere; these waves at synchronous orbit (GOES 2) were observationally confirmed and theoretically discussed by Yumoto and Saito (1983) and Yumoto et al. (1984, 1985a). Figure 4a shows an example of GOES 2 magnetic pulsation data in the (*HP*, *HE*, *HN*) coordinates. The *HP* axis is taken parallel to the spin axis of the satellite, which is approximately perpendicular to the solar-ecliptic plane. The *HE* axis is taken radially inward toward the center of the earth through the satellite. The *HN* is defined by $\mathbf{HN} = \mathbf{HP} \times \mathbf{HE}$. Therefore, the *HP*, *HE*, and *HN* components approximately give the total, radial, and azimuthally westward components of magnetic pulsations near the magnetic equator, respectively. Both compressional in the *HP* component ($\delta B_{\parallel}$) and transverse magnetic pulsations in the *HE* and *HN* components ($\delta B_{\perp}$) with broad frequency spectrum exist simultaneously in the dayside magnetosphere. The amplitude of the compressional Pc 3–4 waves in the *HP* component at $L = 6.67$ is smaller than that of the transverse Pc 4–5 oscillations in the *HE* and *HN* component, but it is generally larger than that of low-latitude Pc 3–4 pulsations observed simultaneously at SGC ($L = 1.8$) near the satellite's meridian (Yumoto and Saito, 1983). Figure 4b indicates scatter plots of the amplitude of compressional Pc 3–4 waves against the IMF cone angle. Pc 3–4 events from 1100 to 1400 LT (near the occurrence peak) are illustrated in the figure. The weak negative correlation of the compressional Pc 3–4 activity detected at GOES 2 is in agreement with those of low-latitude Pc 3–4 pulsations observed at separated ground stations (cf. Fig. 3, Yumoto et al., 1985a). The correlation between the frequency of the transverse oscillations in the *HE* and *HN* directions at GOES 2 and the IMF intensity could not be recognized, whereas scatter plots of the dominant frequency of compressional waves in the daytime (0800–1700 LT from Jan. 27, to Feb. 16, 1981) was found to be related to the IMF magnitude. The distribution in the bottom right panel shows a range limited by the two lines of $f = 4.5\ B_{\text{IMF}}$ and $f(\text{mHz}) = 7.5\ B_{\text{IMF}}(\text{nT})$.

Yumoto et al. (1984) recently inferred the spacecraft-frame frequency (f_{sc}) of magnetosonic upstream waves. The phase velocity of the waves is $V_{\text{ph}}^2 \sim V_{\text{A}}^2\,(1 + f_{\text{o}}/f_{\text{ci}}) \sim V_{\text{A}}^2$, where f_{o} is the plasma frame frequency, $f_{\text{ci}} = eB_{\text{IMF}}/m_{\text{i}}c$ is the local ion cyclotron frequency, and V_{A} is the Alfvén speed. The waves are excited by an anomalous Doppler-shifted ion cyclotron resonance of reflected ion beams in the earth's foreshock. The resonance condition is

$$(f_{\text{sc}}/f_{\text{ci}}) \sim V_{\text{sw}}|\cos\theta_{\text{KV}}|/V_{\parallel}, \tag{3}$$

where V_{sw}, θ_{KV}, and $V_{\parallel}$ are the solar wind speed, angle between $\mathbf{V}_{\text{sw}}$ and the wave vector $\mathbf{k}$, and proton resonant velocity of reflected ion beams in the solar wind frame, respectively (for further details see Tsurutani et al., 1983). Thus, it is resonable to assume a regression line in the form of $f = \alpha_1\ B_{\text{IMF}}$ to represent the data points in Fig. 4b, where $\alpha_1 \sim (V_{\text{sw}}|\cos\theta_{\text{KV}}|/V_{\parallel})e/m_{\text{i}}c$. From observations of ion beam velocity of 650–1,150 km/s (cf. Paschmann et al., 1981; Yumoto et al., 1984), the frequency of the magnetosonic right-handed waves in the spacecraft frame is estimated to be on the order of 0.3–0.5 times the local proton cyclotron frequency (f_{ci}) in the earth's foreshock for $V_{\text{sw}}|\cos\theta_{\text{KV}}| \sim 350$ km/s. The averaged angle θ_{KV} determined by the minimum variance analysis was suggested to be $\cos\theta_{\text{KV}} = -0.8$

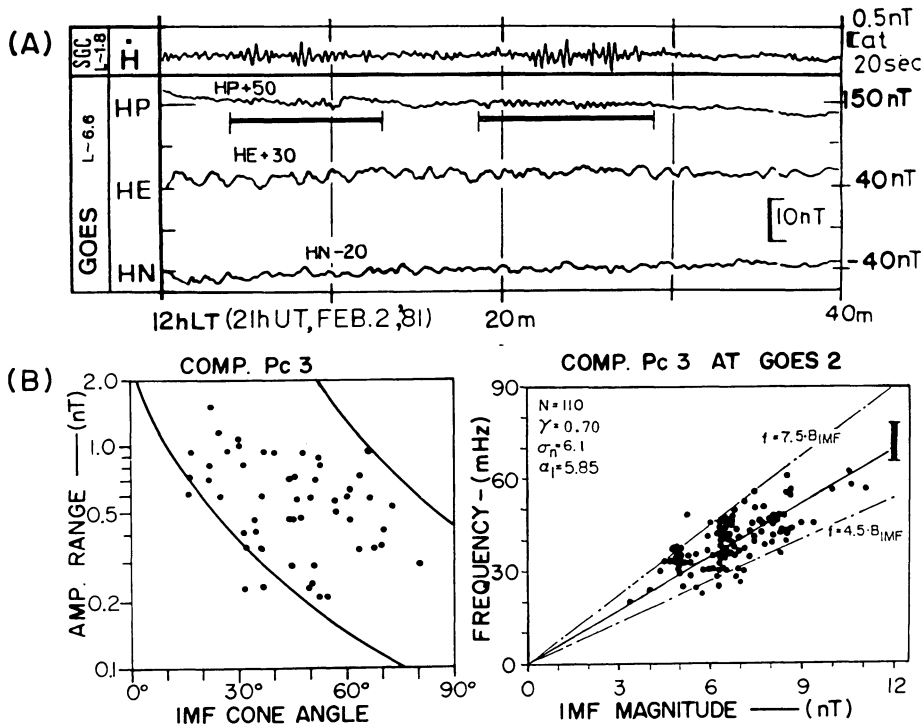

Fig. 4A and B. Compressional Pc 3 waves in the magnetosphere (after Yumoto et al., 1985a). **A** An example of simultaneous records of daytime magnetic pulsations at GOES 2 (L = 6.67) and SGC ground station near the satellite meridian. **B** IMF controls of the amplitude (*left*) and dominant frequency (*right*) of compressional Pc 3 waves in the HP component at the synchronous orbit from January 27 to February 16, 1981

by Hoppe and Russell (1982). It is interesting to note that the range (f_{sc}/f_{ci} = 0.3–0.5) of the inferred frequency of the magnetosonic right-handed waves in the earth's foreshock is in excellent agreement with the range of data distribution bounded by $f = 4.5\ B_{IMF}$ and $f = 7.5\ B_{IMF}$ (Fig. 4b). This observation supports the idea that the magnetosonic right-handed waves in the earth's foreshock are convected across the magnetosheath to the magnetopause, and transmitted into the magnetosphere without significant changes in spectra, and that they are observed as the compressional Pc 3–4 waves at the synchronous orbit.

Yumoto and Saito (1983) and Yumoto et al. (1984, 1985a) observationally clarified the occurrence probability, the correlation coefficient and the standard deviation of frequency of Pc 3–4 pulsations observed at globally separated low-latitude stations ($L < 2.0$) against the compressional Pc 3–4 waves at synchronous orbit. The low-latitude Pc 3–4 pulsations observed at the ground near the GOES 2 longitude were found to have a higher occurrence probability and a smaller standard deviation than those at stations well separated from the longitude. Hence, the compressional Pc 3–4 waves were concluded to propagate mainly in the radial direction toward the earth's center (Yumoto et al., 1985a). The larger frequency deviations at the separated stations were explained by a finite longitudinal region ($\Delta\lambda \sim \pm$ 10°) where the compressional wave propagates, and suggest the existence of various resonant HM oscillations coupled with the compressional source waves in the plasmasphere. From the satellite-ground comparisons for pulsation data, Holló and Verő (1985) also concluded that the low-latitude pulsation activity is more evident than that at L = 6.6 in the magnetosphere and there are differences in the pulsation spectra between ground and space, and that it should be due to different propagation and/or excitation mechanism in the inner magnetosphere.

From the theoretical and observational facts, we can construct a scenario in which the daytime-propagating compressional Pc 3, originating in the earth's foreshock, has an important role in the transmission of the solar wind energy into the deep magnetosphere as shown in Fig. 1a (cf., Yumoto and Saito, 1983; Yumoto et al., 1984 and 1985a). Compressional upstream waves in the earth's foreshock propagate and/or are convected through the bow shock, the magnetosheath and the magnetopause, and penetrate into the deep magnetosphere. Transmitted compressional waves (ω_{comp}) with a finite Pc 3 bandwidth from outside the magnetopause can excite high-harmonic standing oscillations (ω_A) of local field lines in the outer magnetosphere and a fundamental standing oscillation (ω_A) just outside the plasmapause, i.e., in the plasma trough. The ω_{comp} waves can further propagate into the inner magnetosphere and couple with various HM oscillations as discussed in the next section.

2.6 Characteristic frequencies of various Pc 3 oscillations in the plasmasphere

Compressional Pc 3 waves (i.e., fast magnetosonic wave) can propagate across the ambient field into the plasmasphere and can couple with surface waves at the plasmapause, trapped oscillations, and/or eigen oscillations of local field lines at low latitudes in the plasmasphere (Yumoto and Saito, 1983).

Transverse magnetic pulsations in the Pc 3 frequency range near the plasmapause are theoretically expected to consist of the standing field-line oscillations in the plasma trough and the collective eigen mode of surface waves on the plasmapause (e.g., Lanzerotti et al., 1973; Fukunishi and Lanzerotti, 1974a, b). The frequency of the surface eigen mode is given approximately by

$$\omega_{CE} = \sqrt{2}\, k_{\parallel} V_A^{II} \tag{4}$$

where V_A^{II} is the Alfvén velocity just inside the plasmapause (Chen and Hasegawa, 1974b; Lanzerotti et al., 1974). The

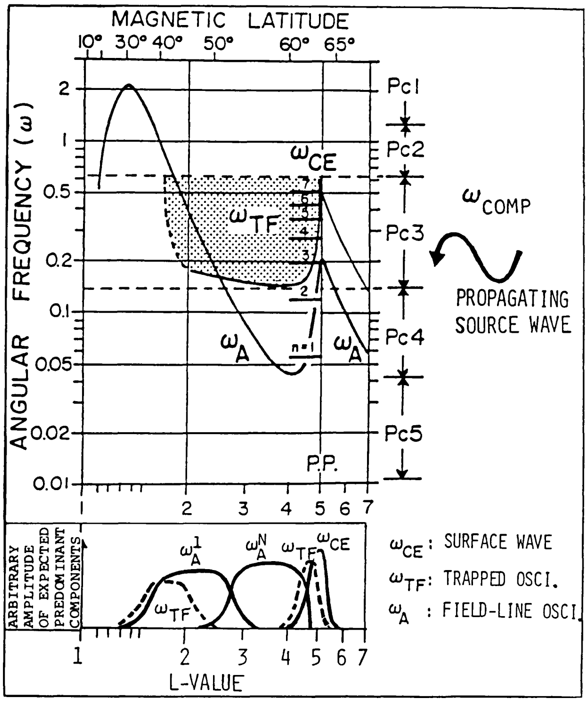

Fig. 5. Characteristic frequencies of coupled HM resonance oscillations in the plasmasphere (after Yumoto and Saito, 1983). Compressional Pc 3 waves, propagating from the earth's foreshock, (ω_{comp}) can couple with the collective surface wave (ω_{CE}) on the plasmapause, trapped oscillation (ω_{TF}) of fast magnetosonic wave in the Alfvén trough, and fundamental and high-harmonic standing field-line oscillations (ω_A^n) in the plasmasphere

value of $k_{\parallel}$ is decided by the length of local field line (l), i.e., $k_{\parallel} = n\pi/l$ 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. 5. Therefore, Pc 3 pulsations excited by the propagating compressional source waves on the plasmapause are expected to be a high harmonic of the collective eigen mode of the surface waves. The 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 also couple with the fundamental collective eigen oscillation on the plasmapause by means of the nonlinear resonance mechanism (Yumoto and Saito, 1982). The condition of the nonlinear resonance is expressed by

$$\omega_{comp} = \omega_r + \omega_2^{fs}, \tag{5}$$

where ω_{comp}, ω_2^{fs}, and ω_r are frequencies of the propagating compressional wave in the outer magnetosphere, one component of HM noise near the plasmapause, and the collective eigen oscillation (ω_{CE}), respectively. In another possible case for the nonlinear resonance excitation of magnetic pulsations inside the plasmapause, ω_{comp}, ω_2^{fs}, and ω_r can be frequencies of the propagating compressional wave from the outer magnetosphere, a trapped oscillation of fast magnetosonic wave, and a standing oscillation of local field lines in the plasmasphere, respectively.

Inside the plasmapause, part of the propagating compressional waves can be trapped within the Alfvén speed trough from the plasmapause to a near 1.7 L value. Discrete frequency spectra (ω_{TF}) of the trapped oscillations are determined mainly by the radial distance of the Alfvén trough. The period of trapped oscillations of the fast magnetosonic wave, which propagates nearly in the equatorial plane in the Alfvén trough region (Doobov and Mainstone, 1973; Tamao, 1978), is given approximately by

$$T_{trapped} \lesssim (2\Delta L/V_{g\perp}) \sim 2\Delta L[V_A^2(k_{\parallel}^2 + k_{\perp}^2)/k_{\perp}^2]^{-1/2} \lesssim 2\Delta L/V_A, \tag{6}$$

where ΔL is a distance between the two peaks of Alfvén velocity and $V_{g\perp}$ stands for the group velocity of a fast magnetosonic wave normal to the ambient magnetic field in the plasmasphere. The estimated periods of trapped oscillations are indicated in Fig. 5. If $\Delta L = L_{pp} - 1.7 = 2.5\ R_E$ and $V_g \sim V_A \sim 800$ km/s, the period of trapped oscillation becomes $\lesssim 40$ s. These trapped oscillations are recently theoretically discussed to couple into standing field-line oscillation by Kivelson and Southwood (1985). They suggested that coupled field-line resonance oscillations occur on the magnetic shell where the transverse mode dispersion relation is satisfied, but the spectrum is dominated by the eigen frequencies of trapped oscillations.

In the plasmasphere, the compressional Pc 3 source waves which have predominantly a **k** vector normal to the ambient magnetic field, can also couple directly with standing oscillations of local field lines (see references of Yumoto, 1985b). The linear coupled oscillations can occur only when the resulting dispersion laws satisfy the following equations:

$$(\omega_{comp}^2 - \omega_{eigen}^2) = [V_A^2(k_{\parallel}^2 + k_{\perp}^2) - (2\pi/T_{eigen}^n)^2] = 0, \tag{7}$$

where $k_{\parallel}$ and $k_{\perp}$ are parallel and normal components of the source's wave vector to the ambient magnetic field and T_{eigen}^n is a n-th "harmonic" eigen period of the standing field-line oscillation. Figure 5 illustrates eigen frequencies (ω_A) of the guided toroidal mode against L value for the gyro-frequency plasma model in the daytime magnetosphere, which were numerically obtained by Yumoto et al. (1983a). 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 $n_i \sim 2000\ cm^{-3}$ at $L \sim 2$ (Orr and Matthew, 1971). Low- and mid-latitude pulsations in the Pc 3 frequency range are concluded to appear mainly as a fundamental at $L = 1.7$–2.6 and a higher harmonic standing oscillation at $L = 2.0$–L_{pp}, respectively (see Fig. 5).

Orr and Hanson (1981) and Gough and Orr (1984) also considered a simplified model of forced field-line oscillations in the magnetosphere of $L = 2$–12, which indicates the latitudinal variation of pulsation phase on the ground. In their model, each individual flux tube responds independently to the driving force of a fast mode HM wave, and then brings about forced damped transverse oscillations. They concluded the latitudinal extent of a mid-latitude Pc 3–4 resonance region being $\lesssim 3°$ for typical value of the damping factor in the daytime ionosphere.

On the other hand, Poulter et al. (1984) suggested that since the low-latitude geomagnetic field is not expected to be significantly distorted by the solar wind, the observed diurnal period variations in the Pc 3 range should be determined by changes in the ambient plasma density. They had applied a physically realistic plasmaspheric model (Fig. 6b) along the $L = 2.3$ flux tube to the determination of eigen periods of standing field-line oscillation over a 24-h interval. The resulting model-pulsation periods are largest during the day with minimum and maximum values at 0500 and 1800 LT, respectively, as shown in Fig. 6a. The model predicts a general increase in the eigen periods during the re-

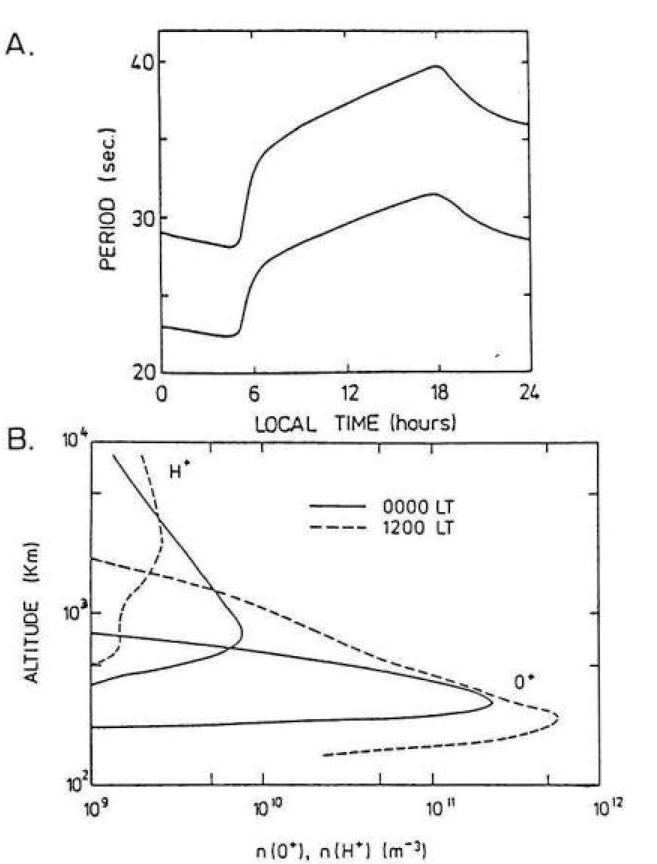

Fig. 6 A and B. Diurnal period variation of low-latitude pulsations (after Poulter et al., 1984). **A** Diurnal eigen period variation of the guided poloidal- (*upper curve*) and toroidal-mode (*lower curve*) fundamental standing oscillations at $L = 2.3$. **B** Realistic plasmaspheric O^+- and H^+-number density models along the $L = 2.3$ flux tube at 0000 LT and 1200 LT

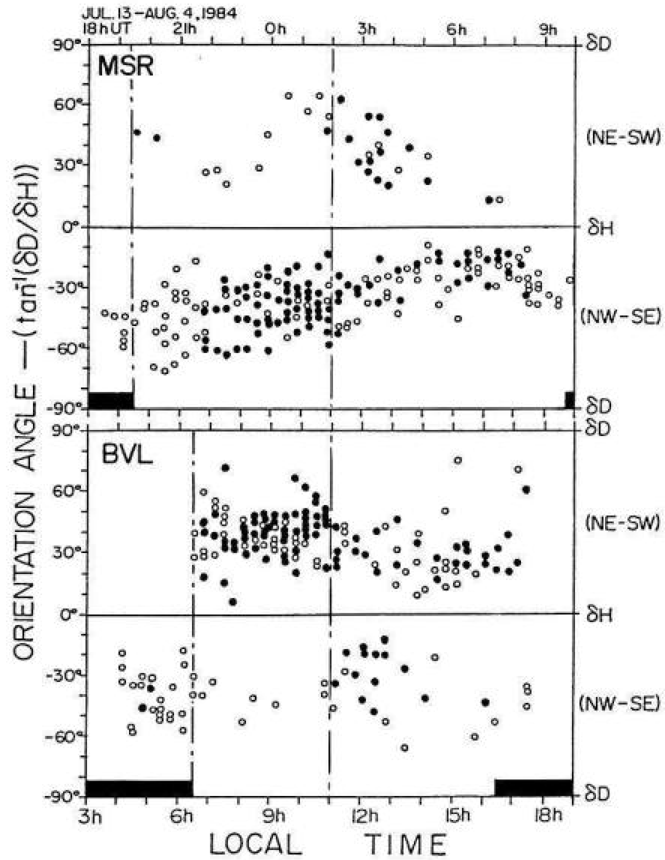

Fig. 7. Diurnal variation of the major axis orientation of low-latitude Pc 3 polarization ellipses in the H-D plane detected at low-latitude conjugate stations ($L \sim 1.5$) (after Yumoto et al., 1985b). *Solid thick lines* indicate the nighttime ionosphere. The orientation angle of the major axis from the H axis toward NE-SW (NW-SE) quadrant is represented as positive (negative). *Solid dots* imply an orientation reversal of the major axis between the northern and southern conjugate stations

plenishment of the protonosphere after a period of geomagnetic activity.

In the lower panel of Fig. 5, arbitrary amplitude of expected predominant components of the excited oscillations (ω_{CE}, ω_{TF}, ω_A^n) are summarized as a function of the L value. Low-latitude Pc 3 pulsations observed at $1.2 < L \lesssim 3.0$ on the ground are believed to be a superposition of these coupled resonance oscillations in the plasmasphere. We are now analyzing pulsation data at low-latitude conjugate stations in order to examine which components of the oscillations dominate on the ground, i.e., to clarify whether the observed low-latitude Pc 3 pulsations are just the propagating compressional Pc 3 waves originating in the outer magnetosphere or the coupled resonance oscillations between the compressional source waves and the trapped, fast magnetosonic waves and/or fundamental and higher harmonic eigen oscillations of local field lines in the plasmasphere. In the next section, we will show preliminary works on wave characteristics of low-latitude Pc 3 magnetic pulsations observed at conjugate stations.

2.7 Wave characteristics of low-latitude Pc 3

From polarization analysis of magnetic pulsations observed simultaneously at northern and southern conjugate stations, we can examine whether the observed pulsations are odd and even modes of standing field-line oscillations (Sugiura and Wilson, 1964) or not resonant field-line oscillations. Although diurnal variations of the conjugate magnetic polarizations are related to the ionospheric conductivity condition in both hemispheres (cf. Yumoto et al., 1985b), propagation characteristics in the azimuthal direction can also be inferred statistically.

In order to clarify wave characteristics of low-latitude Pc 3 magnetic pulsations, Yumoto et al. (1985b) recently statistically analyzed pulsation data of rulfmeters (ring-core-type ULF fluxgate magnetometer) at conjugate stations, i.e., Moshiri in Japan and Birdsville in Australia ($L \sim 1.5$). Amplitude variations of 20 min–1 h duration of the low-latitude Pc 3 were found to occur simultaneously at the conjugate stations. The global behavior in activity of the low-latitude Pc 3 pulsations must be controlled by the cone angle of the IMF (see Verö, 1985). Diurnal amplitude variations of the low-latitude Pc 3 which appears primarily in the morning hours were demonstrated to be related to the shaded and sunlit ionospheres.

Figure 7 shows the diurnal variation of low-latitude Pc 3 polarizations in the H-D plane at the conjugate stations with a L value of 1.5. Top and bottom panels indicate major axis orientations at the northern and southern conju-

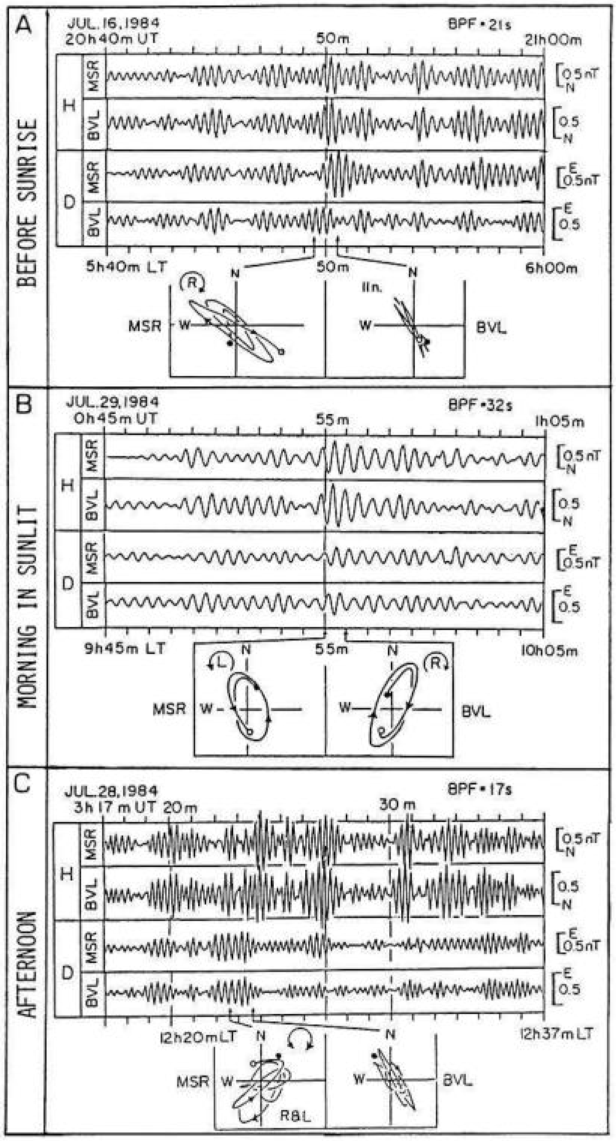

Fig. 8 A–C. Typical examples of simultaneous amplitude-time records of low-latitude Pc 3 at conjugate stations ($L \sim 1.5$) (after Yumoto et al., 1985 b). Hodograms in the H–D plane at Moshiri and Birdsville are illustrated in the lower panels; **A** before sunrise, **B** "mirror" polarization in the sunlit morning, and **C** in the afternoon

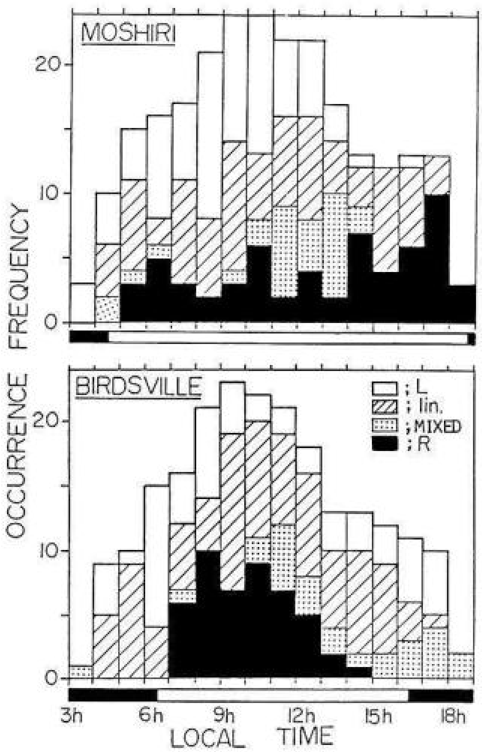

Fig. 9. Diurnal variation of low-latitude Pc 3 polarization senses in the H–D plane detected simultaneously at the conjugate stations ($L \sim 1.5$) (after Yumoto et al., 1985 b). Open, shaded, dotted, and solid areas indicate left-hand, linear, mixed, and right-hand polarizations from a view looking down onto the earth in each hemisphere, respectively

gate stations, respectively. The solid thick line in the figure stands for the nighttime ionosphere determined by the ionospheric f_oE data near the stations. Two transitions for Pc 3 polarizations can be seen. Before sunrise, when the southern ionosphere is still dark, the major axis is in the same northwest-southeast quadrant in both hemispheres. After sunrise, when both the conjugate ionospheres are in sunlit, the major axes are predominantly oppositely directed at the conjugate stations. Moreover, the sense of Pc 3 polarizations at the conjugate stations tends to be reversed.

Typical examples of simultaneous amplitude-time records and Pc 3 polarizations at Moshiri and Birdsville before sunrise, in the sunlit morning, and in the afternoon are illustrated in Fig. 8 a, b, and c, respectively. The polarization relation in the sunlit morning is mirrorlike and is consistent with the expected polarization of odd-mode standing field-line oscillations near a L value of 2.0 (see Sect. 2.6). After 0630 LT, Pc 3 waves which would have a smaller normal wave number than a parallel one (i.e., $k_{\parallel} < k_{\parallel}$), are believed to be effectively reflected at both ionospheres; standing oscillations of local field lines then occur predominantly near $L = 1.7 - 2.6$ (cf. Yumoto and Saito, 1983; Poulter et al., 1984). Dominant periods of standing oscillations at $L = 1.5$ were predicted to be in the Pc 1–2 range as shown in Fig. 5. The observed Alfvén-type Pc 3 pulsations at $L \sim 1.5$ are believed to be associated with the standing field-line oscillations at $L = 1.7$–2.6.

Saka et al. (1980) showed that the increase of D/H ratio (amplitude ratio of D- to H-component) of low-latitude Pc 4 pulsations at $L = 1.16$ appears to coincide with the E-layer ionization enhancement associated with sunrise. However, Yumoto et al. (1985 b) could not find the increase of D/H ratio of low-latitude Pc 3 at the conjugate stations of $L \sim 1.5$. It is believed that the E-layer ionization enhancement is responsible only for the aburpt changes of observed Pc 3 polarization senses and major axes at sunrise at the conjugate stations.

The other transition between polarization types is found to appear near local noon. The low-latitude Pc 3 polarizations at the conjugate stations ($L \sim 1.5$) change from predominantly left-handed (right-handed) in the NW-SE (NE-SW) quadrant to predominantly right-handed (left-handed) in no specific quadrant at $\sim$1100 LT near local noon in the northern (southern) hemisphere (see Figs. 7, 8, and 9). Lanzerotti et al. (1981) and Fraser and Ansari (1985) also pointed out that the polarization reversal of low-latitude Pc 3 at $L \sim 2.0$ occurs near local noon and the orientation of major axis of polarization ellipses changes from a predominantly NW-SE direction in the local morning to a mixed NW-SE/NE-SW direction in the afternoon. Since the ionospheric conductivity changes smoothly near local noon (see Fig. 4 of Takeda and Maeda (1980)), the transition cannot be explained by the ionospheric variation. This transition may be associated with either the propagation or the generation mechanism of Pc source waves in and/or outside the magnetosphere. The lack of a simple pattern of diurnal variation of low-latitude Pc 3 polarizations as shown in Fig. 9 indicates the existence of multiple propagation and/or coupling mechanisms of Pc source waves with various HM oscillations in the inner magnetosphere (see Sect. 2.6.).

By using 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 $L=3.0$ and $L=1.8$–2.7, respectively. Figure 10 shows statistical diurnal variation of the azimuthal wave number at $L \sim 3.0$. We can see that the longitudinal phase propagation changes from westward in the morning to eastward in the afternoon sector. Thus, Pc 3 source waves in the magnetosphere are believed to propagate statistically in the opposite directions. Magnitudes of the azimuthal wave number at $L \sim 3.0$ are comparable in the morning and afternoon sector (Fig. 10). However, Saito et al. (1984) recently demonstrated that in the afternoon sector incoherent wave packets of Pc 3 are predominantly simultaneously observed at longitudinally separated stations at $L \lesssim 2.0$ within $\sim 10°$ in longitude, implying larger azimuthal wave numbers ($m \gtrsim 35$). Hughes et al. (1978) also showed that the sign of azimuthal wave numbers of magnetic pulsations observed simultaneously on the three geostationary satellites changes near noon, and that strong pulsations in the afternoon are detected with low coherence, implying large azimuthal wave numbers. These Pc 3 pulsations of large azimuthal wave numbers (i.e., $k_\perp > k_\parallel$) in the afternoon and evening would be less reflected along the field line in both the northern and southern ionospheres and then would show incoherent wavepackets on the ground as shown in Fig. 8c. The pre- and postnoon asymmetry of azimuthal wave number of Pc 3 pulsations may be associated with the reason why an evening effect similar to the sunrise effect as shown in Fig. 7 could not be found in the low-latitude Pc 3 polarizations at the conjugate stations at $L \sim 1.5$.

However, we cannot yet explain why the azimuthal wave number of Pc 3 source waves is larger in the afternoon than in the morning sector. The morning-afternoon asymmetry of Pc 3 characteristics may be associated with the dawn-dusk asymmetry of Pc 5 pulsations observed in the outer magnetosphere, i.e., azimuthally transverse and radially compressional modes appear predominantly in the dawnside and duskside magnetospheres, respectively (Kokubun, 1981, 1985; Yumoto et al., 1983b). Further theoretical and observational studies are needed to clarify the cause of the dawn-dusk polarization asymmetry of low-latitude Pc 3 magnetic pulsations.

On the basis of these observational and theoretical results, we could construct a possible propagation mechanism for exciting Pc 3 pulsations at $L=1.5$–L_{pp} as shown in Fig. 11. Magnetosonic upstream waves in the earth's foreshock can penetrate into the inner magnetosphere and be observed as compressional Pc 3 waves at synchronous orbit.

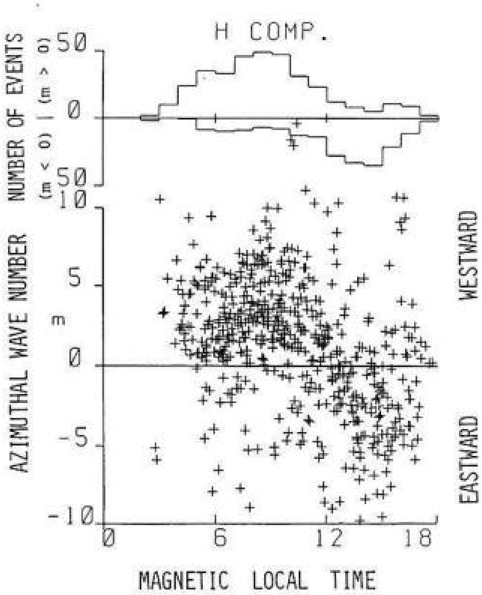

Fig. 10. Azimuthal wave number of Pc 3 pulsations detected at the AFGL network stations of $L \sim 3.0$ (after Saka and Kim, 1985). Number of events (upper panel) and azimuthal wave number $[m]$ (lower panel) are illustrated as a function of magnetic local time. Positive and negative m values indicate westward and eastward longitudinal propagation, respectively

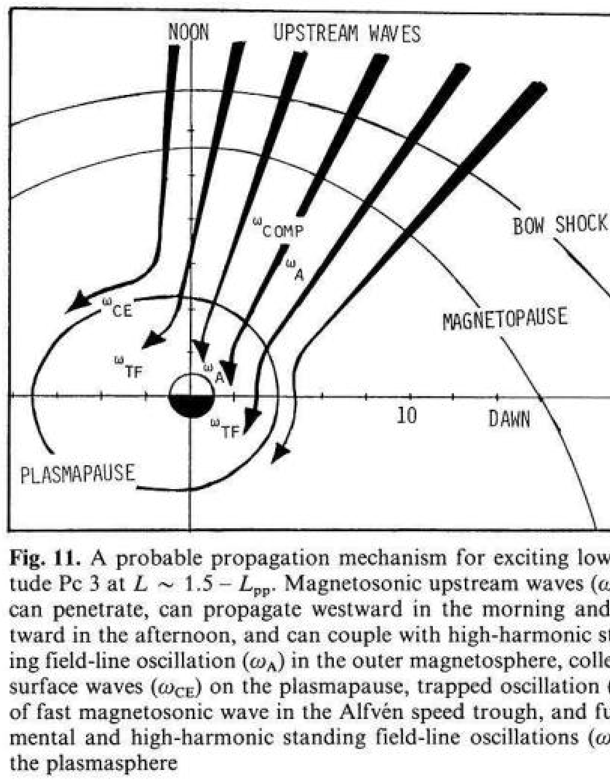

Fig. 11. A probable propagation mechanism for exciting low-latitude Pc 3 at $L \sim 1.5 - L_{pp}$. Magnetosonic upstream waves (ω_{comp}) can penetrate, can propagate westward in the morning and eastward in the afternoon, and can couple with high-harmonic standing field-line oscillation (ω_A) in the outer magnetosphere, collective surface waves (ω_{CE}) on the plasmapause, trapped oscillation (ω_{TF}) of fast magnetosonic wave in the Alfvén speed trough, and fundamental and high-harmonic standing field-line oscillations (ω_A) in the plasmasphere

These transmitted Pc 3 source waves could further propagate predominantly westward in the morning and eastward in the afternoon sector, and then could couple into surface waves on the plasmapause, trapped oscillations in the plasmasphere, and standing field-line oscillations at low latitudes. Pc 3 pulsations observed on the ground at $L=1.5$–L_{pp} would be a superposition of these hydromagnetic reso-

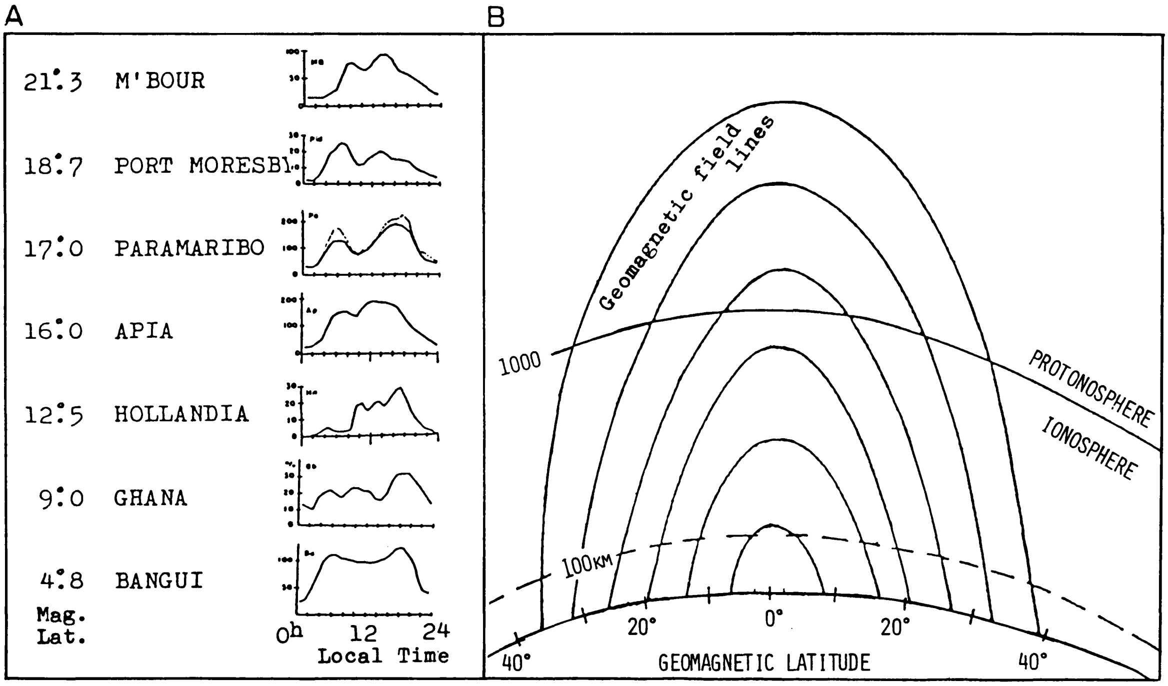

Fig. 12A and B. Pc 2–3 pulsations observed at very low latitudes ($\Phi \lesssim 22°$, $L < 1.2$). **A** Diurnal variation of Pc 2–3 activity at latitudes lower than 22°, summarized by Saito (1983). **B** Magnetic field lines of force illustrated as a function of magnetic latitudes. In the ionosphere ion-neutral particle collisions dominate and thus HM field-line oscillations are believed to be effectively damped (Prince and Bostik, 1964)

nance oscillations in the plasmasphere as shown in Fig. 5; however, further coordinated observations of low-latitude Pc 3 are needed to clarify which modes of various HM waves dominate in the plasmasphere.

2.8 *Pc 2–3 at very low latitudes* ($\Phi < 22°$)

In the preceding, we reviewed mainly the low-latitude Pc 3 magnetic pulsations which are associated with HM resonance oscillations at $L = 1.5$–3.0. On the other hand, Pc 2–3 pulsations detected at very low latitudes ($\Phi < 22°$) are not yet sufficiently clarified either observationally or theoretically. Saito (1983) compared diurnal variations of Pc 2–3 occurrences at many stations in the different periods (cf. Romañá and Cardús, 1962; Romañá, 1962; Hutton, 1960). The evening maximum of Pc 3 activities is a peculiar feature noted only in the subtropical region of approximately 5°–20° in geomagnetic latitude as shown in Fig. 12a. The evening maximum of very low latitude Pc 3 at $\Phi < 20°$ is inconsistent with the local-noon maximum of Pc 3 pulsations which are believed to originate predominantly from the upstream waves in the earth's foreshock at $L = 1.5$–3.0 (cf. Figs. 9, 10). Therefore, Siato (1983) proposed a candidate of endogenic Pc 2–3 source in the equatorial ionosphere.

Pc 2–3 pulsations at $L < 1.2$ may be caused by endogenic ionospheric currents and/or exogenic compressional waves filtered out through the low-latitude ionosphere (Jacobs and Watanabe, 1962; Prince and Bostick, 1964; Greifinger and Greifinger, 1965). Geomagnetic field lines at lower latitudes are illustrated as a function of geomagnetic latitude in the right panel of Fig. 12. The boundary between the magnetosphere and the ionosphere was estimated to be about 1,000 km above the ground (cf. Prince and Bostick, 1964; Saka, 1985). It is noteworthy that the magnetic field lines anchoring below 22° in magnetic latitude are almost entirely in the ionosphere, and thus not easy to oscillate like a standing field-line oscillation in the magnetosphere. Therefore, we can conclude that low-latitude Pc 3 pulsations observed at $\Phi < 22°$ in magnetic latitude are not associated predominantly with a HM resonance oscillation in the plasmasphere. Kuwashima et al. (1979) pointed out that the diurnal variation of very low latitude Pc 3 polarizations at Chichijima ($\Phi = 17.1°$, $\Lambda = 208.9°$) is different from that of low-latitude Pc 3 observed simultaneously at Memambetsu (34.0°, 208.4°), where Pc 3 polarization changes from predominant left-handed in the morning to predominant right-handed in the afternoon (consistent with low-latitude Pc 3 polarization at the conjugate station, Moshiri at $L \sim 1.5$; see Fig. 9). Yumoto (1986a) and Saito et al. (1986) recently demonstrated that diurnal variations of Pc 3 polarization senses at northern and southern low-latitude stations ($|\Phi| \sim 10°$–$20°$) are opposite to those at the conjugate low-latitude stations ($\Phi \sim \pm 35°$; cf. Fig. 9) in the sunlit hemisphere. They suggested the possibility that the low-latitude Pc 3 polarization can be explained by the azimuthally propagating, ionospheric, Pedersen eddy currents induced by inductive electric field of compressional Pc 3 waves at very low latitudes (cf. Yumoto, 1986a; Yumoto et al., 1986).

As one possible exogenic candidate for the generation of very low latitude Pc 2–3, a filtering action of the region between topside and bottomside ionosphere for transversely propagating compressional waves was proposed by Jacobs and Watanabe (1962). By using the filtering mechanism, Prince and Bostick (1964) predicted frequency-power spectra of Pc 2–3 pulsations at very low latitudes. The structure between the topside and bottomside ionosphere and the particle parameters, e.g., integrated ion-neutral particle collisions, were demonstrated to control directly and effectively the attenuation and phase velocity of the transmitted compressional waves. On the other hand, diurnal variation of f_oF_2, which indicate mostly the feature of total electron content (T.E.C.) in the ionosphere, at very low latitudes shows the "noon bite-out" in ionization (cf. Anderson, 1973; Rajaram, 1977). This "noon bite-out" feature is very similar to the occurrence pattern of the very low latitude Pc 2–3 as shown in Fig. 12a (cf. Saito, 1983). Recently, Chao (personal communication, 1985) also demonstrated that the postnoon peak of Pc 3 occurrence at Chung-Li (Φ = 13.8°) during the declining phase of sunspot number is consistent with that of the T.E.C. obtained by satellite differential Doppler measurements, although Pc 3 activities at mid latitudes bear an anticorrelation to increase in F2-region electron concentrations (Verõ and Menk, 1986). The T.E.C. is generally considered to be proportional to ionization. If the T.E.C. would be inversely proportional to ion-neutral particle collisions, the good correlation between the postnoon peaks of Pc 3 occurrence and the T.E.C. at Chung-Li can be explained by the filtering action for transversely propagating compressional Pc 3 waves through the very low latitude ionosphere (cf. Prince and Bostick, 1964).

However, the ionospheric parameters at very low latitudes show magnetic activity, diurnal, latitudinal, seasonal, and solar cycle dependences (cf. Rajaram, 1977). Further theoretical studies and simultaneous conjugate observations of Pc 2–3 pulsations and ionospheric variations at very low latitudes ($\Phi < 22°$, i.e., $L < 1.2$) are needed to clarify the existence of endogenic and/or exogenic source waves near the equator, and then to understand completely the propagation and generation mechanisms of low-latitude Pc 3 magnetic pulsations.

3. Low-latitude Pi 2 magnetic pulsations

3.1 Introduction

Pi 2 magnetic pulsations (damped pulsations with 40–150-s periods) associated with substorm expansion onsets or intensifications have been widely researched by a number of scientists. The main morphological characteristics were established in the 1960s and 1970s (see Siato, 1969; Jacobs, 1970; Orr, 1973; Lanzerotti and Fukunishi, 1974; Southwood and Stuart, 1980; McPherron, 1980). However, by using extensive magnetometer chains and multisatellite data, considerable attention has been recently refocused on completely understanding the global feature of Pi 2 pulsations (see Hughes, 1983; Samson and Rostoker, 1983; Baumjohann and Glassmeier, 1984; Verõ, 1985). Pi 2 pulsations are generally interpreted as a transient hydromagnetic signal associated with a sudden change in the physical state of the magnetosphere at substorm expansion onset. The sudden change is caused by a short-circuiting of the cross-tail current to the auroral oval via field-aligned currents, i.e., by the formation of a substorm current wedge (McPherron et al., 1973; Mallinckrodt and Carlson, 1978; Sakurai and McPherron, 1983). The Pi 2 transient HM signal associated with the sudden formation of field-aligned currents in the magnetotail is believed to play an important role in the dynamic coupling between the magnetosphere and the ionosphere.

However, occurrence and wave characteristics of Pi 2 on a global scale, especially concerning low-latitude Pi 2, have not yet been sufficiently studied and thus are not completely understood. Here, we would like to restrict our considerations to the unresolved problems associated with the generation and propagation mechanisms of low-latitude Pi 2 pulsations. The associated characteristics will be described in Sect. 3.2, and recent theoretical models for generation and propagation mechanisms of Pi 2 pulsations will be reviewed in Sects. 3.3 and 3.4. On the basis of the morphological and theoretical results, a possible model for daytime Pi 2 will be proposed in the final Sect. 3.5.

3.2 Unresolved characteristics of Pi 2 pulsations

Firstly, we summarize only important characteristics which give a clue to the unresolved generation and propagation mechanisms of low-latitude Pi 2, i.e., (1) Pi 2 polarization distribution as a function of local time and magnetic latitude, (2) latitudinal and longitudinal dependences of azimuthal wave numbers, (3) simultaneous occurrence of daytime Pi pulsations, and (4) equatorial enhancement of daytime Pi 2 pulsations.

1. Pi 2 polarization. The morphology of Pi 2 polarization is not quite so simple as shown in Fig. 13 (cf. Saito, 1969). High-latitude Pi 2 pulsations have mostly right-handed polarization toward the pole and left-handed toward the equator of the Pi 2 maximum in the premidnight sector (Samson and Rostoker, 1983; Lester et al., 1985), and vice versa in the postmidnight sector (Kuwashima, 1978; Kuwashima and Saito, 1981; Samson and Harrold, 1983). At midlatitudes from ~56° to ~43°N geomagnetic latitude, i.e., $L \sim 3.2$–1.9, the polarization of Pi 2 is predominantly left-handed, independent of local time (Rostoker, 1967; Lanzerotti et al., 1974; Fukunishi, 1975; Mier-Jedrzejowicz and Southwood, 1979; Baranskiy et al., 1980; Novikov et al., 1980; Samson and Harrold, 1983; Lanzerotti and Medford, 1984; Lester et al., 1984). The predominant left-handed polarization of mid- and low-latitude Pi at all longitudes was believed to be associated with westward propagation from the nighttime source region (Green and Stuart, 1979; Mier-Jedrzejowicz and Southwood, 1979; Lester et al., 1983). Samson (1985) proposed that the midlatitude left-handed polarization could be explained as a direct result of high-latitude, field-aligned current propagating westward. On the other hand, Lanzerotti and Medford (1984) suggested that the low-latitude Pi 2 observation is difficult to interpret straight-forwardly in the context of hydromagnetic wave resonance theory where the plasmapause responds to only one of the source frequencies. Southwood and Hughes (1985) recently proposed that superposition of two waves with different amplitude, travelling in opposite direction is required to produce the polarization characteristic of midlatitude Pi 2.

At very low latitude ($L \lesssim 1.5$), Kato et al. (1956), Sakurai (1970), and Sutcliffe (1981) reported that low-latitude Pi 2 has right-handed and left-handed polarizations prior to and after local midnight, respectively. These observations are also difficult to interpret by using the existing theories, which were constructed to explain mainly high- and mid-latitude Pi 2 pulsations, e.g., the substorm current wedge model (Lester et al., 1983). Further coordinated simultaneous observations at separated stations of 70°–0° in mag-

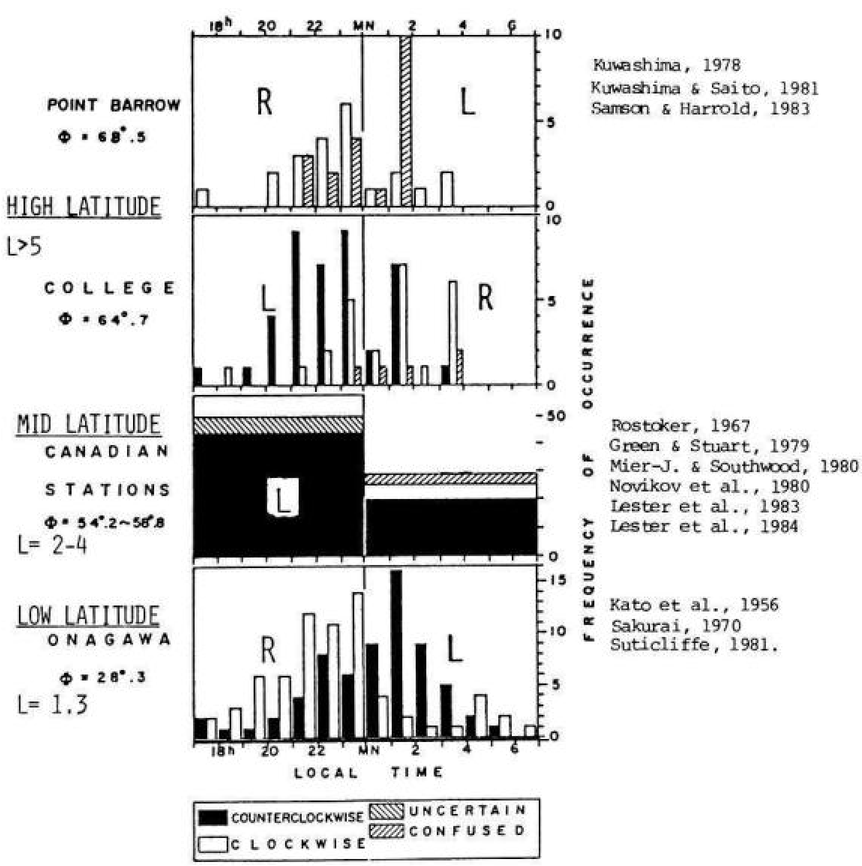

Fig. 13. Latitudinal and longitudinal dependences of nighttime Pi 2 polarizations, obtained by adding the results of many workers to the original figure of Sakurai (1970). Open, shaded, and solid areas indicate right-handed, mixed, and left-handed polarizations in the H–D plane from a view looking down onto the earth, respectively

netic latitude are needed at all local times to clarify the unresolved problem.

2. Azimuthal wave number of Pi 2. Samson and Harrold (1983) suggested that elliptical polarizations at high latitudes were caused by azimuthal expansion of the oscillating field-aligned current associated with Pi 2. The spatial motion of substorm electrojets and the region of Pi 2 localization is as much as 1,000–2,000 km westward in 10 min, i.e., 1.5–3.0 km/s, implying large apparent azimuthal wave number (e.g., $|m| \sim 20$–40 for a Pi 2 period of 150 s). However, Samson and Harrold (1985) recently reported that the phase velocities of high-latitude Pi 2 from the University of Alberta are eastward to the east of the region of the onset of the field-aligned currents, and westward to the west of the region of the onset. They estimated that the westward velocities are extremely high, approximately 20–50 km/s (i.e., $|m| \sim 2.4$–7.2 for 100–150-s periods), which are likely not correlated with motion of the westward surge.

Lester et al. (1985) also demonstrated that apparent azimuthal wave number of high-latitude Pi 2 near the eastward electrojet at $\Phi = 60°$–70° is $|m| \sim 8$, which is larger than the average wave number ($|m| \sim 2$–4) at midlatitudes ($\Phi \sim 40°$–55°) (see Green and Stuart, 1979; Mier-Jedrzejowicz and Southwood, 1979; Lester et al., 1983, 1984). The phase propagation of Pi 2 observed at SMA and AFGL network stations was reported to be westward at all geographic latitudes of 28°–71°, and was generally believed to be associated with the westward movement or expansion of the equivalent ionospheric current vortex (Pashin et al., 1982) and an oscillating field-aligned current system (Samson and Rostoker, 1983) after the breakup. However, Lester et al. (1984) recently found that from estimates of signal phase differences between station pairs, westward propagation of midlatitude Pi 2 dominates west of and within the field-aligned current meridians but eastward propagation dominates east of the current system.

At very low latitudes ($L \lesssim 1.5$), east-west phase variations have not yet been examined sufficiently in the east-west chain system. The top panel in Fig. 14 shows an example of simultaneous records of low-latitude Pi 2 magnetic pulsations obtained at Onagawa ($\lambda = 141.5°$E, $L = 1.30$), Ewa Beach ($\lambda = 202.0°$E, $L = 1.15$), and San Gabriel Canyon ($\lambda = 242.0°$E, $L = 1.83$). Time lags of the first impulse in the H component between the two low-latitude stations, i.e., ONW-EWA and SGC-EWA, are illustrated with the local times of the stations in the bottom panels. Broken lines indicate the least squares fitting a straight line in the data. The result suggests that low-latitude Pi 2 pulsations observed near midnight would propagate westward during premidnight and eastward during postmidnight. Apparent propagating velocities in the longitudinal direction can be estimated to be $\sim 5.3°$/s (~ 530 km/s) and $\sim 4.5°$/s (~ 450 km/s) at the low-latitude ground stations ($L = 1.15$–1.83). These faster longitudinal velocities correspond to smaller azimuthal wave numbers of $m = 360° * \Delta T / (\Delta\Phi \cdot T) \sim 0.4$–2 for wave period of $T = 40$–150 s, where ΔT is time lag and $\Delta\Phi$ (=40°–60°) is longitudinal distance between two stations. The apparent opposite propagation of low-latitude Pi 2 pulsations may be associated with the polarization reversal across the midnight as shown in Fig. 13. On the other hand, low-latitude (and/or equatorial) Pi 2 pulsations appear even during the daytime on many

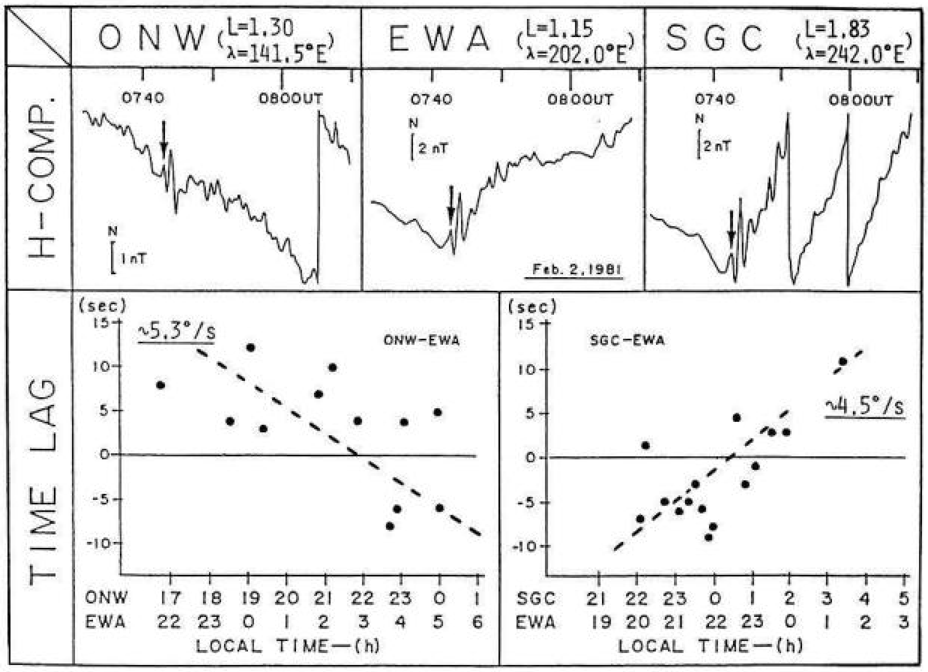

Fig. 14. Phase relations of low-latitude Pi 2 pulsations observed simultaneously at longitudinally separated stations, Onagawa (ONW, λ = 141.5°E), Ewa Beach (EWA, 202.0°E), and San Gabriel Canyon (SGC, 242.0°E). Upper and lower panels show an example of simultaneous amplitude-time records of low-latitude Pi 2 pulsations and phase lags of the first impulse of Pi 2 detected simultaneously at ONW and EWA and at SGC and EWA, respectively (after Saito et al., 1981)

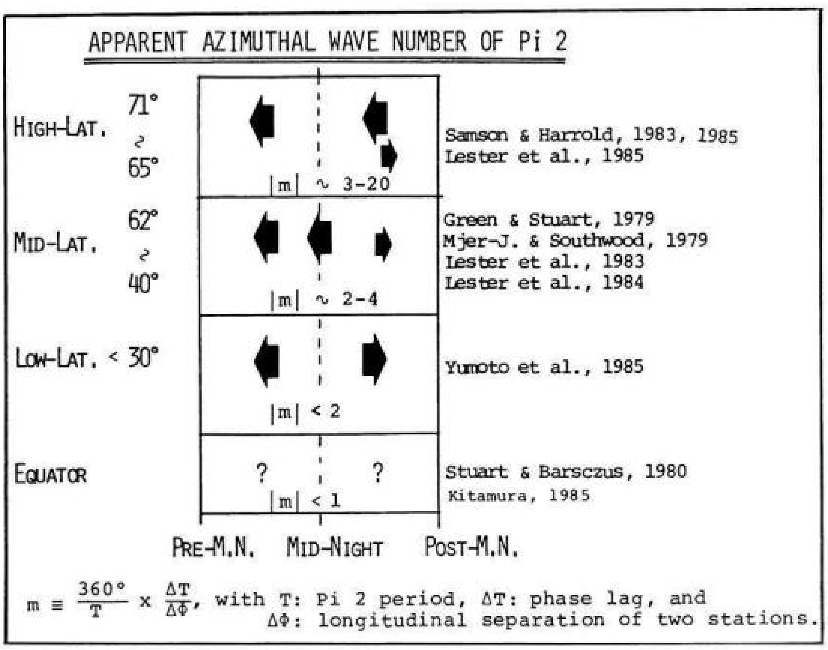

Fig. 15. Summary of apparent azimuthal wave numbers of Pi 2 pulsations obtained at high, middle, low and equatorial latitudes by many workers. Solid arrows indicate apparent longitudinal propagation direction

occasions in simultaneity, within the accuracy of comparison (± 30 s), with the onset of magnetospheric substorms in the night hemisphere (Grenet et al., 1954; Yanagihara and Shimizu, 1966; Saito et al., 1976b; Sakurai and Saito, 1976; Stuart and Barsczus, 1980; Sastry et al., 1983), implying small apparent azimuthal wave number ($|m| < 1$). Kitamura (personal communication, 1985) recently suggested that since no phase lag between daytime and nighttime Pi 2 pulsations could be detected at Fukuoka, Japan, and Maroa, Cameroun, near equatorial latitude, the azimuthal wave number of Pi 2 pulsations near the equator would be zero.

It is noteworthy that the apparent azimuthal wave numbers of Pi 2 have a latitudinal dependence, i.e., $|m| \sim 3$–20 at high latitudes, $|m| \sim 2$–4 at mid and low latitudes, and $|m| < 1$ at very low latitudes as summarized in Fig. 15. Further theoretical studies are needed to explain why the azimuthal wave number of Pi 2 depends on magnetic latitudes.

3. Simultaneous occurrence of daytime Pi pulsations. There are very few reports showing evidence of the possibility of Pi 2 observed during the daytime (cf. Table 3b of Kato et al., 1960, 1961). Yanagihara and Shimizu (1966) examined the simultaneous occurrence of daytime Pi 2 at equatorial latitude by using rapid-run magnetograms from Koror and Guam in the daylit hemisphere and Fredericksburg in the night hemisphere. They found that of 112 Pi 2's

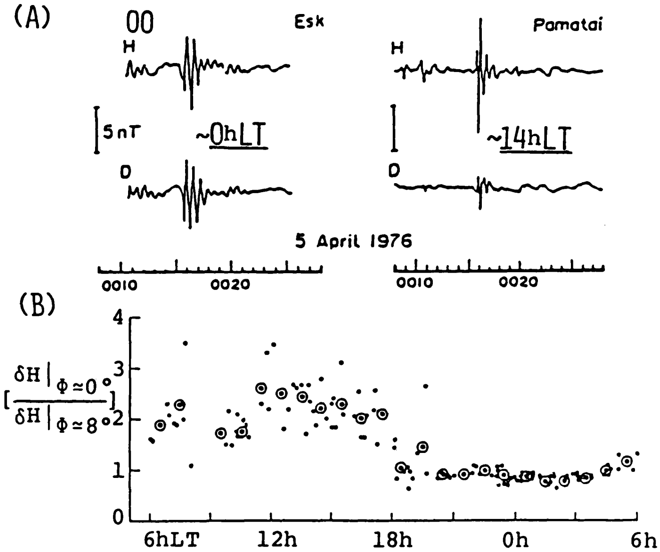

Fig. 16A and B. Daytime Pi pulsations. **A** An example of Pi pulsation observed simultaneously at ~0015 UT on April 5, 1976, at Pamatai ($\lambda = 149.5°$W) and at Eskdalemuir (3.2°W) (after Stuart and Barsczus, 1980). **B** Local time variation of Pi amplitude at equatorial latitude ($\Phi \sim 0°$) normalized by that at off-equatorial latitude ($\Phi \sim 8°$) (after Sastry et al., 1984)

observed during the night, 74 could be identified at the daytime equatorial station. Within the accuracy of comparison ($\pm$ 30 s), daytime Pi's occur simultaneously with their nighttime counterparts (Fig. 16a; Stuart and Barsczus, 1980). The dominant spectral component is generally at a shorter period than the current nighttime Pi 2, which is in agreement with a selective response of the low-latitude field lines to a transient, as described by field-line resonance theory. Yumoto et al. (1980) also demonstrated that about 40% of Pi 2 pulsations observed at the midlatitude Fredericksburg station in the night sector correspond with Pi pulsations identified at the low-latitude Onagawa station in the daylit hemisphere.

The lack of large and systematic differences of the arrival time over the globe suggests that a transient change occurs simultaneously all through the magnetosphere, and that the differences in character of the Pi 2 pulsations are associated with local regions of critical response to the change in magnetospheric condition.

4. Equatorial enhancement of daytime Pi 2. Yanagihara and Simizu (1966) showed that when Pi's are observed during the daytime their amplitudes near the dip equator are enhanced by a factor of between 2 and 5 relative to those at Kakioka, on the same longitude but at 26°N. The appearance of Pi on the dayside of the earth was reported to be limited to a narrow latitude band around the geomagnetic equator (Stuart and Barsczus, 1980). Sastry et al. (1983) demonstrated that Pi 2 does appear even during the daytime on many occasions at equatorial latitudes in simultaneity with the onset of magnetospheric substorms at AE stations located in the night hemisphere. They also showed the daytime enhancement of observed Pi amplitudes in H at the dip equator. The local time variation in the ratio of H amplitudes at the equator of $\Phi = -0.6°$ to those at the off-equator of $\Phi = 7.5°$ during daytime appears to indicate the possible influence of equatorial electrojet on the Pi signals (Fig. 16b). In view of this, the enhancement of daytime Pi could be described by the enhanced ionospheric conductivity in the equatorial electrojet region.

Although it is almost certain that Pi 2 originates in association with auroral zone current systems (or transient changes in them), there is considerable uncertainty about how its effects are transmitted across field lines both latitudinally and longitudinally into the nighttime and daytime equators. In the following sections, recently proposed Pi 2 models for generation and propagation mechanisms, related to the above-mentioned four characteristics, will be reviewed.

3.3 Wave and current fluctuation models for Pi 2 generation

Theories of the generation mechanism of Pi 2 magnetic pulsations have been categorized physically, basically into two groups: one group primarily concerns with the wave resonance theory, and the other group concerns with the current fluctuation theory. Although no one still knows conclusively which groups of Pi 2 pulsations really predominate in the magnetosphere, recently proposed Pi 2 models can be reviewed as follows:

1. Transient-response wave model. Transient-response mechanisms are considered to interpret the observed Pi 2 pulsation as large-amplitude Alfvén wave, i.e., odd mode standing oscillation of auroral field lines, launched by a sudden change in the magnetospheric convection and/or configuration (Stuart, 1974; Maltsev et al., 1977; Saito et al., 1976a; Olson and Rostoker, 1977; Kuwashima and Saito, 1981). The launched Alfvén wave is believed to be subsequently damped by the ionosphere during reflection (Newton et al., 1978; Gough and Orr, 1984; Glassmeier et al., 1984; Kan and Sun, 1985). The transient response in the magnetosphere-ionosphere coupling has been studied by many researchers.

Nishida (1979) showed that a constant current source in the plasma sheet can produce a transient response in the ionospheric electric field, resembling the Pi 2 signature. Kan et al. (1982) suggested that the transient response to a step function voltage source in the magnetosphere can also produce an overshoot damped oscillation at the nonuniform ionospheric conductivity. Two-dimentional models of the magnetosphere-ionosphere coupling were analyzed by Lysak and Dum (1983) for the temporal development of the current and voltage sources. Expected electric and magnetic field variations on the ground are illustrated for both current and voltage generators in Fig. 17 (cf. Baumjohann and Glassmeier, 1984). Sun and Kan (1985) represented a two-dimensional model of the transient response in which the ionosphere electric field and current are calculated from the successive reflections of Alfvén waves launched in opposite directions toward both the ionospheres by enhanced convection in the plasma sheet. By matching the field-aligned current density of the incident and reflected Alfvén waves to the field-aligned current density due to the divergence of the ionospheric current driven by the electric field of the waves (Kan et al., 1982; Glassmeier, 1983; Ellis and Southwood, 1983), they have shown that the damped oscillatory nature of Pi 2 pulsations observed on the ground can be produced by the transient ionospheric response to an enhancement of the convection in the plasma sheet.

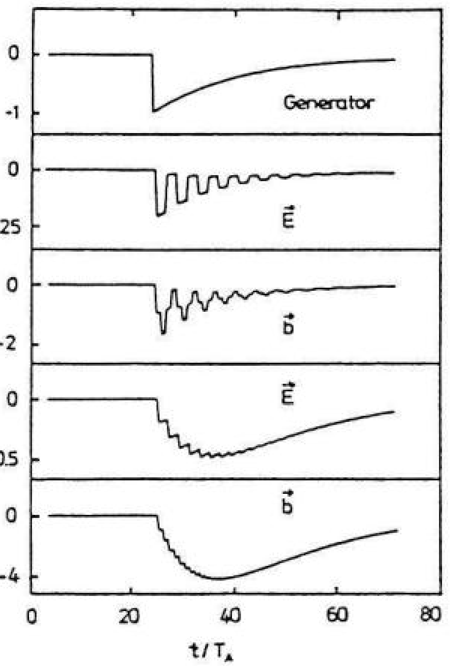

Fig. 17. Development of the magnetic field in the magnetosphere and the electric field in the ionosphere after a current (voltage) generator is switched on in the magnetotail (cf. Baumjohann and Glassmeir, 1984). The upper time series represents the generator function; the following two traces show the electric and the magnetic field if a current generator is switched on; the lower two traces show electric and magnetic field for a voltage generator. T_A is the travel time of the impulse between the equatorial plane and the ionosphere. The amplitudes of the fields are normalized to the value of the generator field just after it has been switched on

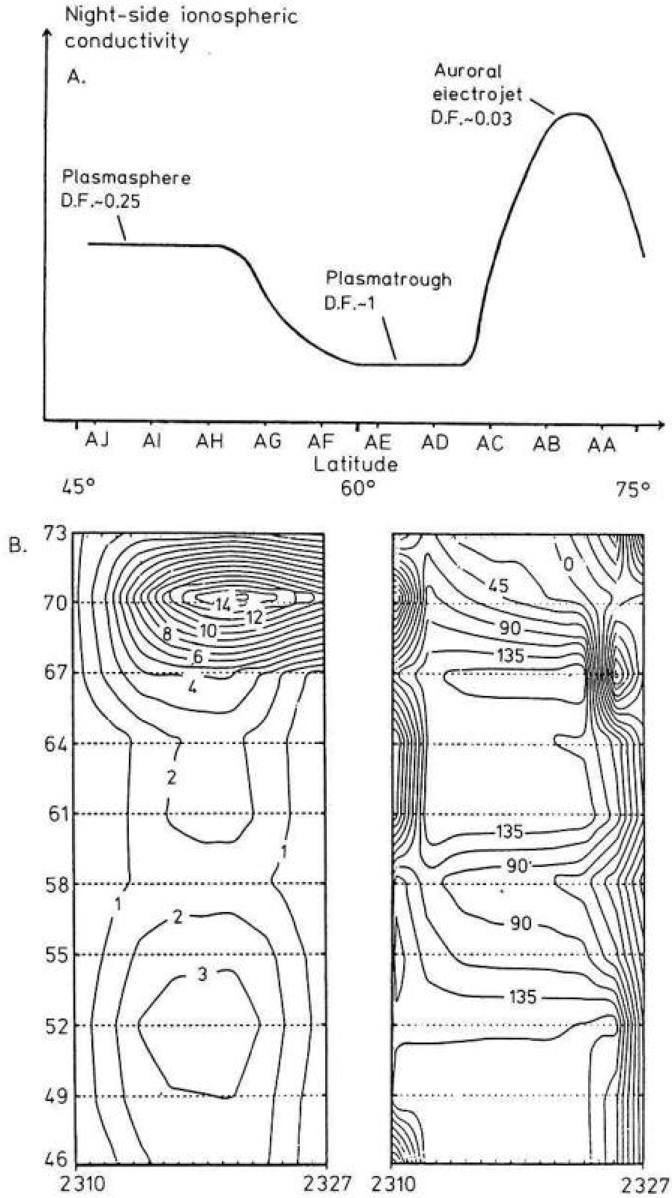

Fig. 18A and B. Individual field-line oscillations driven by forced damped simple harmonic motion in the magnetosphere (Gough and Orr, 1984). **A** The assumed variation of nighttime ionospheric conductivity and the appropriate damping factors (D.F.) versus latitude. **B** Amplitude (left) and phase contours (right) of the forced oscillations for nighttime condition are illustrated as a function of latitude

Gough and Orr (1984) analyzed individual field-line oscillations of the magnetosphere responding independently to a monochromatic driving fast mode force, i.e., a kind of the transient response mechanism. Assuming the variation of nighttime ionospheric conductivity with latitude of 46°–72° and the appropriate damping factors, they successfully demonstrated the latitudinal profile of amplitude and phase changes of the forced damped oscillations in the magnetosphere. The results of the high-latitude resonance and lower-latitude near-resonance conditions near the plasmapause are illustrated in Fig. 18.

Lester et al. (1984) recently reported that although the sense of horizontal polarization of midlatitude Pi 2 is predominantly left-handed at all longitudes, the westward propagation dominates west of and within the substorm-associated, field-aligned current meridians, but the eastward propagation dominates east of the substorm current system. These observed polarizations at midlatitude cannot all be explained by either a purely westward wave or a purely standing wave. In order to interpret the polarization characteristics of midlatitude Pi 2, Southwood and Hughes (1985) recently proposed a superposition of two circularly polarized waves propagating azimuthally in opposite directions with different amplitudes (Fig. 19). The two waves are polarized in the opposite sense. The large-amplitude, left-handed wave is assumed to propagate westward. The eastward wave has a smaller amplitude than the westward propagating one, but the same value of $|\underline{k}|$. Such a pattern could be set up by a partially reflecting boundary which reflects some of the originally westward travelling incident signal. The resultant wave was demonstrated to be left-handed elliptically polarized and to have a net westward phase motion, which is very similar to Pi 2 polarizations observed at midlatitudes (see Fig. 4 of Lester et al. (1984)).

These theoretical considerations and the complex Pi 2 polarization patterns as shown in Fig. 13 suggest that Pi 2 pulsations observed at high, mid, and low latitudes on the ground should consist of various HM resonance (or forced) oscillations at different locations in the magnetosphere. Wave characteristics of the various oscillations depend on local plasma parameters and the magnetospheric structure (cf. Yumoto and Saito, 1983). In order to establish the global transient Pi 2 response in the magnetosphere,

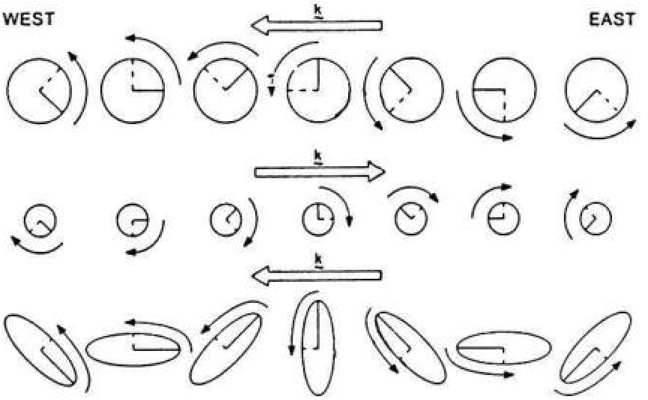

Fig. 19. Southwood and Hughes's (1985) model for midlatitude Pi 2 polarizations. A superposition of two waves, i.e., a left-handed circularly polarized westward wave and a right-handed circularly polarized eastward wave with amplitude half of the westward wave, is similar to Pi 2 polarization patterns at midlatitudes

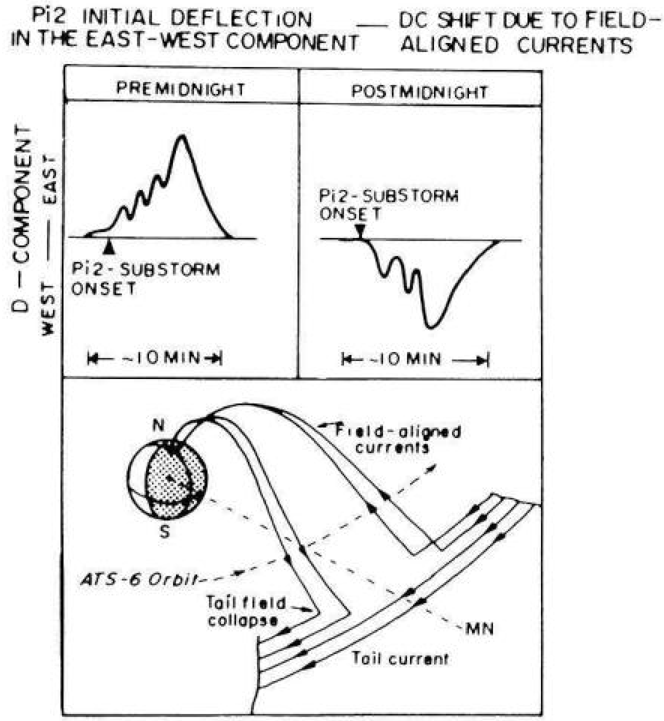

Fig. 20. Schematic representation of initial deflection of Pi 2 wave and dc shift (*top panel*) is interpreted as an effect of the substorm field-aligned currents (*bottom panel*) (after Sakurai and McPherron, 1983)

coordinate simultaneous observations are needed from high latitudes to the equator in both the daytime and nighttime hemispheres.

2. Pi 2 models associated with the substorm current wedge. After substorm expansion onset magnetic energy in the magnetotail is believed to be suddenly released by short-circuiting the enhanced cross-tail current, which is still not conclusively understood (cf. Akasofu, 1977; Nishida, 1978; McPherron, 1979). The geometry of the substorm current wedge in the magnetosphere was proposed by Clauer and McPherron (1974). During substorm expansion onset associated with the sudden disappearance of part of the dawn-dusk-directed cross-tail current, the ionospheric conductivities are believed to be greatly enhanced in the localized breakup region. The inhomogeneously enhanced conductivity causes a southward polarization electric field, which drives a strong westward ionospheric current in the breakup region (cf. Coronitti and Kennel, 1972). The westward ionospheric current is considered to be closed via localized upward field-aligned currents at western edge and wider weaker downward field-aligned currents in the eastside active region.

Sakurai and McPherron (1983) recently examined the relation between the substorm current wedge and Pi 2 polarizations observed at synchronous orbit. They demonstrated that the initial perturbation in the azimuthal component of a Pi 2 event is in the same sense as the perturbations caused by the substorm-associated, field-aligned currents, i.e., positive (eastward) in premidnight and negative (westward) in postmidnight as shown in Fig. 20, and suggested that there may be a very close association between their causative mechanisms. Saito (1986) recently discussed the close association.

In order to understand high- and midlatitude Pi 2 characteristics on the ground, many workers recently tried to apply the substorm current wedge model to transient Pi 2 magnetic pulsations. From detailed observations of Pi 2 characteristics in the auroral zone, Rostoker and Samson (1981) and Pashin et al. (1982) discussed relations among the observed Pi 2 polarizations, oscillating localized field-aligned currents of the westward travelling surge, and equivalent ionospheric currents. Assuming that the periodic

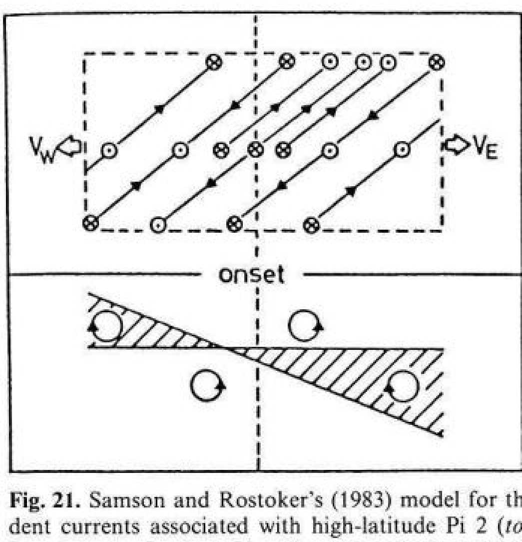

Fig. 21. Samson and Rostoker's (1983) model for the time-dependent currents associated with high-latitude Pi 2 (*top panel*). Different sense of polarizations is produced when the oscillating current system in the top panel expands eastward and westward (*bottom panel*)

fluctuations of particle precipitation in the oscillating upward field-aligned current can generate a periodic change in the ionospheric conductivity distribution with gradients in radial direction only and then also generate a radial electric field, the equivalent Pi 2 current system observable at the ground is expected to be due to the ionospheric Hall current (Pashin et al., 1982). On the other hand, Tamao (1985) and Tamao et al. (1985) evaluated a direct contribution from the horizontal component of oblique field-aligned currents to surface magnetic variations in the auroral re-

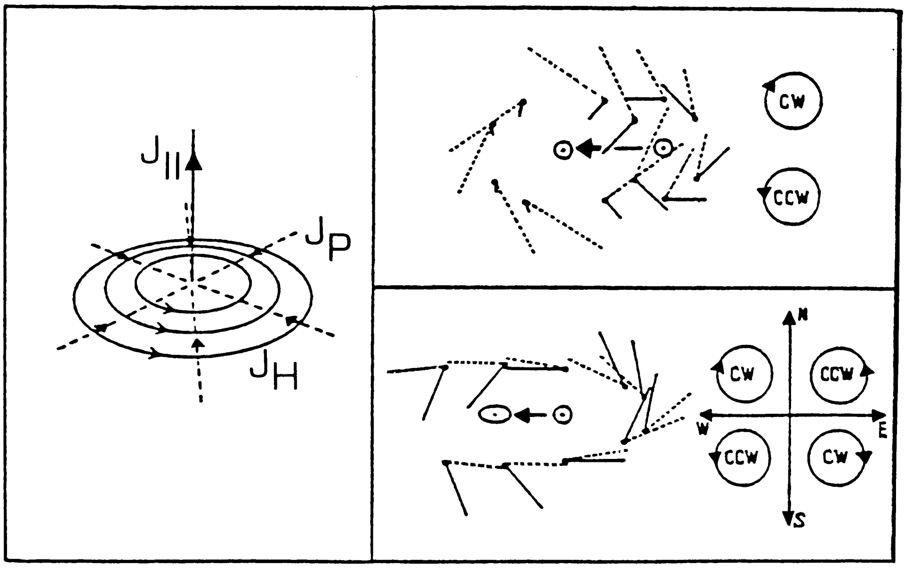

Fig. 22. Pashin et al.'s (1982) model for the ionospheric circular current system associated with high-latitude Pi 2. Schematic representation of Hall (J_H) and Pedersen currents (J_P) associated with localized upward field-aligned current ($J_{||}$) in an ionosphere with uniform conductivity distribution (*left panel*). Two cases of circular and elliptic current distributions separated in space and time producing difffernt polarization features (*right panel*). Current vectors at the earlier and later time are shown by solid and dashed lines, respectively. The right part shows schematically the polarization pattern around the center line if during the westward movement the current strength changes periodically with time

gion, in comparison with that of the ionospheric eddy current associated with a localized electric potential distribution on the horizontal plane. For the localized perturbation with an isotropic horizontal structure at 60° geomagnetic latitude, they demonstrated that the direct contribution attains up to about 80% of the magnetic contribution of the ionospheric Hall current.

Samson and Rostoker (1983) have considered a system of oscillating field-aligned currents expanding eastward and westward as shown in Fig. 21 to explain the high-latitude Pi 2 polarization. The oscillating field-aligned current and the ionospheric Hall electrojet contribute largely to the D- and H-component, respectively. The expected polarization pattern is also illustrated in the figure. On the other hand, due to the westward movement of the region of intense upward vertical field-aligned current and the Pi 2-associated equivalent ionospheric current system of circular shape, a different sense of magnetic polarizations was inferred by Pashin et al. (1982) as shown in Fig. 22. When a circular streamline of the equivalent current at the beginning of the Pi 2 pulsation moves to the west and the streamline changes its form to be an elliptical shape, four quadrants with a different sense of polarization were predicted to appear. This is in good agreement with the more complicated polarization patterns of high-latitude Pi 2 pulsations (Kuwashima, 1978; Samson and Harrold, 1983; see Fig. 13). Pashin et al. (1982) concluded that high-latitude Pi 2 polarizations will strongly depend on the shape, direction, and velocity of the movement of the actual ionospheric current pattern. However, real configuration of current systems in the auroral zone during substorm is more complicated. It is still not clarified which of these Pashin et al.'s and Samson and Rostoker's models are more effective and realistic. The high-latitude Pi 2 polarizations will be able to be interpreted by using both the more sophisticated oscillating field-aligned current and the equivalent Pi 2 ionospheric current in the near future.

Polarization characteristics of midlatitude Pi 2 pulsations were compared with those predicted from the current wedge model by Lester et al. (1983, 1984) (Fig. 23), where the substorm-associated, field-aligned current was assumed to oscillate with Pi 2 period. They demonstrated a good

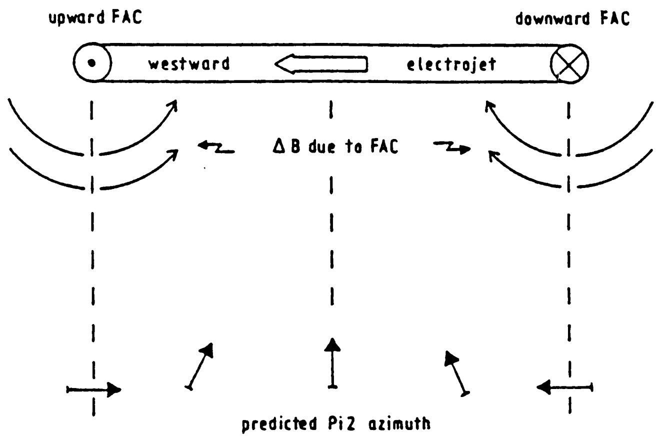

Fig. 23. Lester et al.'s (1983) model for the substorm current wedge associated with mid- and low-latitude Pi 2. A schematic view of the ionospheric and field-aligned portions of the substorm current wedge and the predicted Pi 2 polarization azimuths within the two extreme meridians of the current system are illustrated if the Pi 2 is a result of the oscillation of such a current system

agreement between the observed and the predicted Pi 2 azimuths of horizontal polarization ellipses at midlatitudes. From the comparison between the substorm center determined from the midlatitude Pi 2 azimuth and that determined from the midlatitude bay disturbance associated with the substorm current wedge, they also showed that substorm and Pi 2 current systems are not always collocated. On the other hand, low-latitude Pi 2 polarization reversal near local midnight as shown in Fig. 13 can not yet be conclusively understood by using the present theoretical models. The above-mentioned models of Figs. 21, 22, and 23 have to be modified to explain the low-latitude Pi 2 characteristics.

Magnetic field variations on the ground are believed to be due to the fluctuations of the oblique field-aligned current, oscillating in the Pi 2 frequency range (cf. Tamao, 1985), the coexisting ionospheric eddy currents (cf. Pashin et al., 1982) in the auroral zone, and the ionospheric eddy current induced by Pi 2 wave fields (cf. Tamao, 1984; Glassmeier, 1984). Future theoretical studies are needed to quantitatively examine which contributions from the current fluctuations appear more effective in the magnetic field variations at mid and low latitudes on the ground.

3.4 Model of instantaneous transmission from the polar electric field to the equator

In order to interpret the simultaneous occurrence of daytime Pi and the equatorial enhancement of daytime Pi 2 (cf. Sect. 3.2), we would like to review the propagation mechanisms of Pi 2 pulsations and then introduce a possible candidate in this section.

Magnetic variations of long period ($T \gtrsim 10$ s) without equatorial enhancement, e.g., a positive magnetic impulse (PPI) of SSC at low latitudes, have been recently theoretically considered to be a compressional HM wave transversely propagating from the magnetosphere to low and equatorial latitudes (Kikuchi, 1986), while variations with equatorial enhancement, e.g., main impulse of SSC, are associated with the polar electric field transmitting almost simultaneously to the equator in the vacuum wave guide bounded by the ionosphere and the earth's surface (see Kikuchi and Araki, 1985). On the basis of the existence of daytime Pi's corresponding with nighttime Pi 2's and the equatorial enhancement of daytime Pi's, many authors had suggested that an instantaneous transmission process would occur from high latitudes to the daytime equator as follows: (1) Any hydromagnetic process in the magnetosphere for the transmission of Pi 2, thought to originate at high latitudes in the midnight sector, to the dayside needs a relatively large travel time ($\sim$100 s or more). The propagation velocity and transmitted energy in the Pi 2 frequency range are limited by the HM conditions of the medium (cf. Kikuchi and Araki, 1979a, b). (2) Jacobs et al. (1965) and Rostoker (1965) considered that the electric field or ionospheric current was transmitted one-dimensionally in the uniform E region in explaining the east-west spread of the equivalent current of Pi 2 pulsations. However, the time required for observing an appreciable intensity at the equator is more than 1 h, since the time scale of field variation is proportional to the square of propagation distance (see Kikuchi and Araki, 1979a). The attenuation of transmitted electric field in the ionosphere was also estimated to be about 100 dB/1000 km for a harmonic wave with a period of 100 s (Prince and Bostick, 1964). (3) Almost instantaneous transmissions were considered to be possible in the ionospheric wave guide centered in the F_2 ionization peak; however, the lower cutoff frequency of the wave guide is about 1 Hz (Greifinger and Greifinger, 1968). Therefore, the electric field transmission of our concern is not likely to occur in the F region. (4) Assuming the earth-ionosphere wave guide model as shown in Fig. 24, Kikuchi and Araki (1979b) demonstrated that the TM mode can transmit the polar electric field instantaneously to low latitudes. When the source field has a finite scale in the east-west direction, the transmitted field spreads in the plane of the ionosphere and simultaneously suffers from geometrical attenuation (Fig. 24b). Nevertheless, they concluded that sufficient currents can flow along the daytime dip equator, because the electrical conductivity is anomalously enhanced there (Kikuchi et al., 1978). Models (1), (2), and (3) are impossible to explain the simultaneous occurrence of daytime Pi 2's with equatorial enhancement, whereas model (4) is probable for excitation of daytime Pi 2's near the equator.

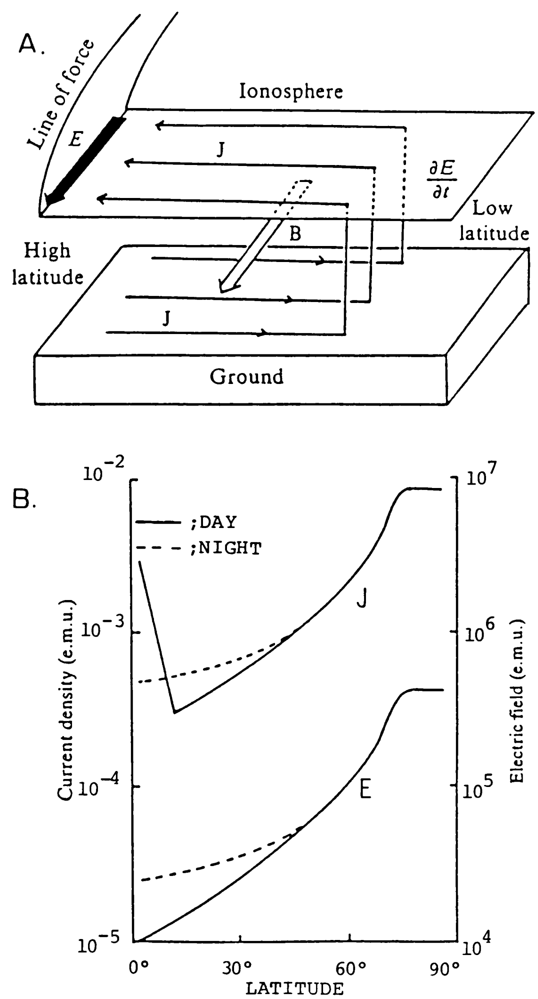

Fig. 24A and B. Model of instantaneous transmission from the polar electric field to the equator (cf. Kikuchi et al., 1978). **A** Horizontal propagation of electric fields impressed on the high-latitude ionosphere through the wave guide between the ionosphere and the earth's surface. **B** Latitudinal variations of electric field, E, and currents, J, at noon (*solid line*) and midnight (*dashed line*). The ionospheric conductivity is assumed to be isotropic and uniform at all latitudes at nighttime and at latitudes greater than 10° at daytime. In the daytime equatorial region, it varies sinusoidally with local time and is maximum at the noon equator

Daytime Pc 3 magnetic pulsations having unclear equatorial enhancements (see Kannangara, 1972) are believed to be associated with the compressional waves, propagating across the magnetosphere and filtered out through the low-latitude ionosphere (cf. Sect. 2.8). We concluded that low-latitude Pi 2 pulsations having the equatorial enhancement during the day (Sastry et al., 1983) can be explained by using model (4) of the equatorial ionospheric current system driven by the instantaneously transmitted polar electric field during substorm expansion onset. In order to establish the daytime Pi 2 transmission model through the ionosphere-earth's surface wave guide, simultaneous magnetic and electric fields observations are needed by using latitudinal and longitudinal chain stations with new techniques of measurement from high latitudes to the equator.

3.5 A possible model for daytime Pi 2

Theoretical scenario on the generation and propagation mechanisms of low-latitude Pi 2 pulsations at $L \lesssim 3$ is not yet constructed, because morphological characteristics of low-latitude Pi 2 have not been established (see Sect. 3.2). The simultaneous occurrence of daytime Pi 2 and the apparent smaller azimuthal wave number of $|m| < 1$ at very low latitudes can not be interpreted by either longitudinal movements (or expansions) of the oscillating field-aligned current (Fig. 21) and the equivalent ionospheric current (Fig. 22) systems in the auroral zone or propagations of HM compressional Pi 2 waves across the magnetospheric field. The apparent longitudinal phase velocity of low-latitude Pi 2 projected on the auroral latitude (i.e., $V_{ph} \sim \pi R_E/mT \sim 200$ km/s for $m=1$ $T=100$ s at $\Phi=60°$) is much higher than the expansion velocity of westward surges (i.e., $\sim$ 1–3 km/s; see Akasofu, 1977). The HM propagation process in the magnetosphere also needs a relatively larger travel time ($\gtrsim$ 100 s). More realistic Pi 2 model has to be constructed.

Figure 25 shows an example of the simultaneous occurrence of daytime and nighttime Pi 2 pulsation observed at mid and low latitudes (cf. Yumoto, 1986b). This is one of the CDAW-6 events studied by Hughes and Singer (1985). The top panel of the figure illustrates ordinary magnetograms at Halley (HY) and the AFGL network stations (TPA, SUB, MCL, CDS, RPC) in the nighttime, and Japanese stations (MMB, KAK, KNY) and Guam in the daytime. The middle panel indicates induction magnetograms at Onagawa (Φ = 28.55°, Λ = 208.14°) in the afternoon sector. The bottom panel shows how Pi 2 polarization hodograms relate to the ionospheric currents computed by Kamide et al. (1983). The daytime Pi 2 hodogram at ONW and nighttime Pi 2 hodograms at the AFGL network stations are superimposed on maps of the ionospheric current vector as a function of the station locations. Although the significant westward electrojet on the postnoon sector is not consistent with the usual DP 2 currents caused by the magnetospheric convection enhancements, it is noteworthy that the major axes at ONW and the AFGL stations approximately point toward the centers of substorm-associated ionospheric currents near 1500 LT and 0100 LT, respectively. The daytime and nighttime low-latitude bay disturbances also agree with magnetic variations caused by the current wedges formed near 1500 LT and 0100 LT, respectively (cf. Lester et al., 1983, 1984; Yumoto, 1986b). Therefore, daytime Pi 2 pulsations are believed to appear with the substorm-associated current wedge formed in the daytime sector.

In order to interpret the result in Fig. 25 and the unresolved problems in Sect. 3.2, i.e., (3) the simultaneous occurrence of daytime Pi 2 and (4) the equatorial enhancement of daytime Pi 2, Yumoto (1986b) proposed a possible daytime Pi 2 model (Fig. 26) as follows: Before and/or during substorm expansion onset, a conventional DP 2 eastward current (or another substorm-associated westward current as shown in Fig. 25c) governed by electric field enhancements, e.g., the magnetospheric convection enhancements, and a substorm DP 1 current caused by a strong conductivity increase appear concurrently in the postnoon-evening and in the midnight sectors, respectively. Nighttime Pi 2 pulsations are generally believed to be excited at the moment when part of the dawn-dusk directed cross-tail current suddenly disappears and after which the substorm current wedge is set up (see Fig. 20). If the sudden change of the cross-tail current could be transferred instantaneously through the three-dimensional current system to the ionospheric current enhanced in the postnoon-evening sector, and thus into a partial ring current in the outer magnetosphere ($L \gtrsim 8$), another transient response could be ex-

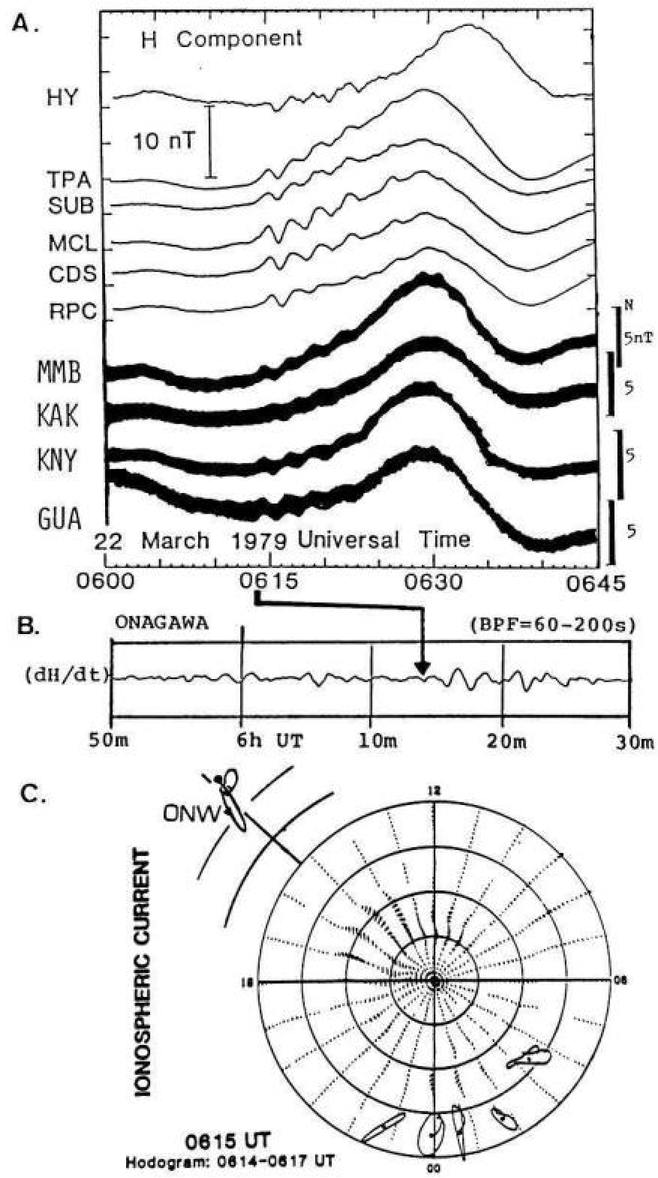

Fig. 25A–C. Relations among daytime and nighttime Pi 2 pulsations, magnetic bay variations, and ionospheric currents. **A** Magnetometer data from Halley (HY) and five of the AFGL network stations in the midnight sector (Hughes and Singer, 1985) and from Japanese and Guam stations in the daytime sector showing the magnetic bay and Pi 2 pulsation signatures of a substorm onset at 0614 UT. **B** Amplitude-time record of daytime Pi pulsation in the induction magnetogram at Onagawa during the CDAW-6 event. **C** Pi hodograms at ONW and the AFGL stations are superimposed on maps of the total ionospheric current vectors (cf. Hughes and Singer, 1985). The maps are in corrected geomagnetic coordinates; circles mark 10° increments of latitude from the pole. Westward electrojets grow in the 0000–0200-LT and 1400–1700-LT sectors which correspond approximately to the centers of the nighttime Pi 2 and the daytime Pi polarization patterns, respectively

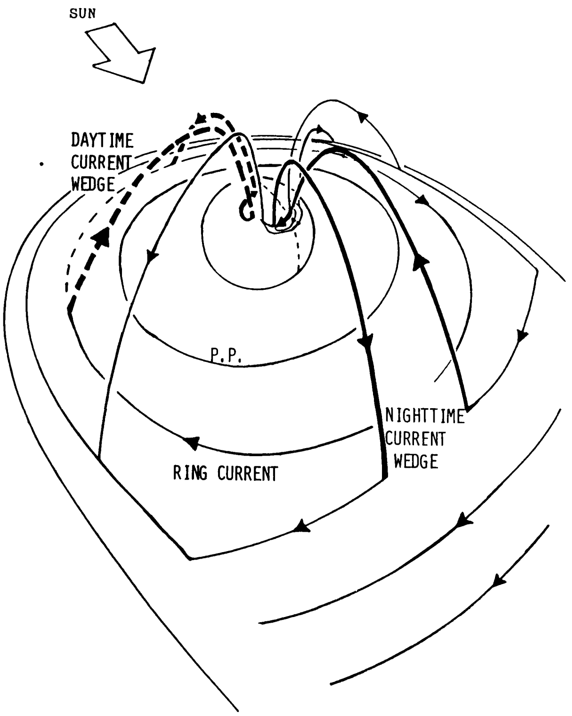

Fig. 26. A possible generation and propagation mechanism of daytime Pi pulsation on the basis of the present observational results and theoretical models. Before and/or during the substorm onset, if an enhanced electric field or currents in the dayside high-latitude ionosphere could become a current wedge system (*dashed lines*) similar to the nightside substorm current wedge (*solid thick lines*), the equatorial enhancement of Pi 2 and the simultaneous occurrence of daytime Pi pulsations can be explained by the combination of the substorm current wedge model (Sect. 3.3) and the instantaneous transmission model of polar electric field (Sect. 3.4)

pected to occur in the daytime sector as illustrated by dotted lines in Fig. 26. The dayside transient response can appear as another substorm-associated current wedge, and as an ionosphere-magnetosphere coupling oscillation in the Pi 2 frequency range at high latitudes (see Fig. 17 in Sect. 3.3). At the same time, if the oscillating electric field enhanced in the postnoon auroral zone could be instantaneously transmitted to the equator, it could produce the equatorial enhancement of daytime Pi 2. This model can explain the two unresolved problems (3) and (4) in Sect. 3.2. However, further simultaneous observations at globally distributed chains of stations are needed to clarify how the dayside substorm current wedge can be set up, and then associated with daytime Pi 2 pulsations.

The unresolved problems (1) and (2) of low-latitude nighttime Pi 2 pulsations have not been yet theoretically studied in the present paper. Pi 2 magnetic pulsations observed at low-latitudes on the ground are believed to be contributed from ionospheric currents, flowing overhead, induced by the electric field transmitted from the polar region through the ionosphere-earth's surface wave guide (cf. Kikuchi et al., 1976b), ionospheric eddy currents induced by Pi 2 wave field in the magnetosphere (e.g., Lysak and Dum, 1983; Gough and Orr, 1984; Southwood and Hughes, 1985) and by the compressional Pi 2 waves filtered out through the low-latitude ionosphere (Prince and Bostick, 1964), and the oscillating field-aligned currents in the auroral zone (cf. Pashin et al., 1982; Tamao, 1985; Samson, 1985). In order to understand the generation mechanism of low-latitude Pi 2 in the nighttime, we must first theoretically and/or observationally clarify which components of the various contributions dominate at low latitudes on the ground.

4. Summary and conclusions

Low-latitude Pc 3 and Pi 2 magnetic pulsations play important roles in the solar wind-magnetosphere interaction and the dynamic coupling of the magnetosphere and the ionosphere. Therefore, investigations of the generation and propagation mechanisms of low-latitude Pc 3 and Pi 2 pulsations are concluded to be indisputable and indispensable in understanding the essential aspects of the solar-terrestrial relationships. The resolved generation and propagation mechanisms and future studies to establish the mechanisms and to clarify unresolved problems can be summarized as follows:

1. Low-latitude Pc 3. Magnetosonic upstream waves excited by the reflected ion beams in the earth's foreshock are convected through the bow shock and the magnetosheath to the magnetopause, transmitting into the magnetosphere, and can be the most probable source of low-latitude Pc 3 pulsations (see Sects. 2.2, 2.3, and 2.5). The propagating compressional Pc 3 source waves can couple with various hydromagnetic oscillations in the inner magnetosphere (Sects. 2.4 and 2.6). At low latitudes of $L \sim 1.5$–3.0, Pc 3 pulsations are theoretically believed to be a superposition of the propagating compressional source waves and the various HM resonance oscillations, e.g., fundamental and high-harmonic standing field-line oscillations and trapped oscillations in the Alfvén trough. The predominant modes of observed Pc 3 at low-latitude conjugate stations ($L \sim 1.5$) were found to depend on both the ionospheric conditions and the propagation characteristics of the source waves (see Sect. 2.7). A possible candidate of Pc 3 pulsations at very low latitudes ($\Phi \lesssim 22°$, i.e., $L < 1.2$) was suggested in Sect. 2.8 to be the filtered-out compressional waves propagating from the outer magnetosphere through the very low latitude ionosphere.

In order to observationally establish the generation and propagation mechanisms of low-latitude Pc 3, simultaneous observations are needed by means of both multiple conjugate stations from high to low latitudes on the ground and multiple satellites in the solar wind near the magnetopause and in the magnetosphere. Simultaneous observations of magnetic and ionospheric variations at longitudinally separated low-latitude stations are also needed to examine the propagation characteristics and predominant modes and to clarify how the ionospheric parameters control the occurrence and wave characteristics of low-latitude Pc 3 pulsations.

2. Low-latitude Pi 2. Although the generation and propagation mechanisms of low-latitude Pi 2 have not yet been clarified, four characteristics, having a clue to the unresolved problems, were pointed out in Sect. 3.2 as follows: (1) Pi 2 polarization distribution as a function of local time and magnetic latitudes, (2) latitudinal and longitudinal dependences of apparent azimuthal wave numbers, (3) simultaneous occurrence of daytime Pi pulsations, and (4) equatorial enhancement of daytime Pi 2. The complex Pi 2 polarization and azimuthal wave number distributions of (1) and (2) imply that observed Pi 2 pulsations consist of multiple magnetic variations, whose characteristics reflect propagation and coupling (or resonance) mechanisms and thus depend on local plasma parameters in the magnetosphere. With respect to the recently published theoretical models (Sects. 3.3 and 3.4), a possible daytime Pi 2 model was proposed to explain the unresolved problems (3) and (4) in Sect. 3.5. The simultaneous formation of a dayside current wedge (see Fig. 26) by the enhanced polar electric field in the postnoon sector before and/or during substorm expansion onset is believed to be a more reasonable explanation for the simultaneous occurrence of daytime Pi and the equatorial enhancement of daytime Pi 2 pulsations.

In order to clarify the unresolved problems and to establish the generation and propagation mechanisms of Pi 2, we also have to carry out an international coordinated simultaneous observation by means both of longitudinally and latitudinally, i.e., worldwide, separated stations and multiple satellites in space.

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