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LOW-LATITUDE Pi 1–2 MAGNETIC PULSATIONS OF THE AUGUST 28, 1986 SUBSTORM EVENT

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Abstract: An isolated substorm occurred at 1153 UT on August 28, 1986 provides an opportunity for studying a relation between low-latitude Pi 1–2 magnetic pulsations in the conjugate area around $L=1.3$–2.1 on the ground and a substorm-associated variation at geocentric distance of 8 R_E near the midplane of the magnetotail. The low-latitude Pi activities on the ground started ~60 s after the onset time of the substorm-associated dipolarization with a possible formation of an X-type neutral line at AMPTE/CCE. The ground H-component pulsation showed a discrete frequency and an amplitude of nearly the same magnitude in a wide area around $L=1.3$–2.1, and its phase propagation was poleward and westward ($m \sim 1.7$) during premidnight. The D-component odd-mode oscillation localized at $L \sim 2.1$ on the ground had the same quasi-monochromatic period (~13 s) as a compressional wave at AMPTE/CCE. These H-component global eigen mode and D-component localized mode may have been associated with a poloidal magnetic oscillation (including the "magnetosphere" cavity resonance mode) and a toroidal standing field-line oscillation excited by the compressional waves with impulsive and quasi-monochromatic components at AMPTE/CCE, respectively.

1. Introduction

Pi 1–2 magnetic pulsations (period=1–150 s) at the expansion phase onset of magnetospheric substorms have been studied with great interest during the last two decades. Pi 2 pulsations, according to the IAGA definition, are long-period pulsations which occur usually at the beginning of magnetic bay disturbances. Pi 1 pulsations are shorter period pulsations which often occur simultaneously with Pi 2. Because of the complex features of Pi 1 pulsations, the generation mechanism of Pi 1 has not yet been fully understood. Early studies of the pulsations based on the data from a small number of ground-based stations clarified the timing between the Pi 2 onsets and substorm expansion phase onsets (HOLMBERG, 1953; KATO *et al.*, 1953; SAITO *et al.*, 1976; SAKURAI and SAITO, 1976). KATO (1965) first found a correlation between substorm-associated magnetic variations (sampled at 5.46 min by IMP-1) in the magnetotail and Pi 2 pulsations observed at low latitude (Onagawa). Subsequent studies established the statistical properties of Pi 2 waves, including amplitude behavior, dynamic spectrum and polarization hodogram (see reviews by SAITO, 1969; JACOBS, 1970; ORR, 1973; LANZEROTTI and FUKUNISHI, 1974; SOUTHWOOD and STUART, 1980; MCPHERRON, 1980). Recent studies with data from multiple stations on the ground and in space extended the study of wave properties, and revealed spatial characteristics in the magnetosphere (see reviews of HUGHES, 1983; SAMSON and ROSTOKER, 1983; BAUMJOHANN and GLASSMEIER, 1984; VERÖ, 1986; YUMOTO, 1986).

Theories proposed for the excitation of high-latitude Pi 2 pulsations generally assume that the oscillatory phenomenon is resulted from a transient response of auroral field lines due to a sudden change in the physical state of the magnetosphere at the time of the expansion phase onset (NISHIDA, 1979; SATO, 1982; LYSAK and DUM, 1983; KAN and SUN, 1985; ROTHWELL *et al.*, 1986). It should be noted that previous observational as well as theoretical studies have been directed toward understanding the excitation of Pi 2 pulsations observed at higher ($L>2$) latitude.

Recent studies of Pi 2 pulsations using ground-based multiple stations have added new morphological knowledge of Pi 2 pulsations. For example, YUMOTO *et al.* (1988a) demonstrated that Pi 2 polarizations at lower latitudes ($\Phi \lesssim 30°$) are right-handed (with reference to the direction of the ambient magnetic field) in the premidnight sector, while it is left-handed in the postmidnight sector. In addition, the azimuthal wave number (m) of the pulsations changes with latitude as $|m| \sim 3$–20 at high latitudes ($L>4$), $|m| \sim 2$–4 at middle latitude ($L \sim 2$–4), and $|m|<2$ at low latitude ($L \lesssim 2$) (see review of YUMOTO, 1986). Pi 2's appear even during the daytime on many occasions at equatorial, low, and mid latitudes in simultaneity with the onset of magnetospheric substorms in the night hemisphere (SUTCLIFFE, 1980; STUART and BARSCZUS, 1980; YUMOTO, 1986, 1987). The transient response model of auroral field lines at high latitudes has not shown how the pulsation propagates from high to low latitude and how the dominant period of low-latitude Pi 2 is determined. No theory is available at the present stage for explaining the observed properties of Pi 2 pulsations at low latitudes.

In the present paper we study the relation between Pi 1–2 pulsations observed on the ground at low latitudes and magnetic field variations observed by AMPTE/CCE in the near-earth tail at the expansion phase onset of a magnetospheric substorm on August 28, 1986. We will confirm that the low-latitude Pi 1–2 pulsations with period of $\sim$10–60 s are excited after $\sim$+1 min of a sudden increase in the northward component of the magnetic field at CCE at geocentric distance of 8 R_E. In the case when a short period ($\sim$13 s) oscillation superimposes on the Pi 2 pulsations, two different modes coexist for wave excitation/propagation at low latitudes. We propose a qualitative model for the observation.

2. Experiments and Data

Ground magnetic data presented in this paper were obtained when a network of stations was operated in Japan-Australia conjugate areas (YUMOTO *et al.*, 1988b).

The stations were located at Asahikawa (ASH; geographic latitude $\phi=43.97°$, geographic longitude $\lambda=142.20°$, $L=1.55$), Onagawa (ONW; 38.43°, 141.48°, 1.30), Birdsville (BSV; −25.83°, 139.3°, 1.55), Dalby (DAL; −27.18°, 151.20°, 1.56), St. Kilda (SKD; −34.70°, 138.50°, 2.11). BSV and ASH are magnetically conjugate, and ONW and SKD are approximately on the same meridian of the conjugate pair. The DAL site is situated near the same latitude and ~12° east in geographic longitude of the conjugate station, BSV. The magnetic field measurements at ASH, BSV, DAL, and SKD were made with ring-core fluxgate magnetometers specially designed for measuring ULF waves (rulfmeter). The measurement at ONW was done with an induction magnetometer. Amplitude and time resolutions of reproduced analog data from the rulfmeter system are 0.07 nT and 0.5 s, respectively.

During the magnetometer campaign, the AMPTE/CCE spacecraft was fortunately located on the nightside (see Takahashi *et al.*, 1987; Yumoto *et al.*, 1989). Magnetic field data from the satellite is used in this study as an indicator of substorm activity. CCE was launched in August 1984 into an elliptical geocentric orbit with an apogee of 8.8 R_E, an inclination of 4.8°, an orbital period of 15.7 h. During the low-latitude campaign CCE had its apogee in the 2330–0230 magnetic local time sector, an ideal location for monitoring the magnetic field variations associated with substorm. Magnetic field at the spacecraft was measured with a fluxgate magnetometer (Potemra *et al.*, 1985), with an original sampling rate of 8.06 vectors per second. We use 6.2 s averages of the data throughout this study, and the vector data will be presented in the dipole VDH coordinate system. In the system, $\hat{e}_H$ is antiparallel to the earth's dipole axis, $\hat{e}_D$ is parallel to $\hat{e}_H \times \hat{r}$, and $\hat{e}_V = \hat{e}_D \times \hat{e}_H$ completes a triad.

3. Observations

Figure 1 shows the magnetic field data obtained concurrently on the ground at ONW and in space at AMPTE/CCE around the time of a substorm onset, *i.e.*, 1153 UT on August 28, 1986. At CCE, the magnetic field had a small northward component B_H ~10 nT until 1153 UT, when it suddenly jumped to ~40 nT. The field change is accompanied by irregular disturbances in all field components. Magnetic field variations of this type have been known to occur at the expansion phase onset in the near-earth tail (McPherron *et al.*, 1973). When the same phenomenon is observed on the equator, the B_H change accompanies a field orientation change from tail-like to dipole-like. Therefore, it is convenient to use the term "dipolarization" to describe the field variation in general. Dipolarization can be understood as the result of a sudden disappearance of the cross tail sheet current from the near-earth portion of the tail. Figure 2 shows the trajectory of AMPTE/CCE when the low-latitude Pi 2 pulsations were detected in the conjugate area in the pre-midnight sector around 21 LT (*i.e.*, 1200 UT).

Near the 1153 UT dipolarization at CCE, the ONW magnetogram showed an onset of an irregular pulsation. The start time of the pulsation was 1154 UT, that is, approximately 1 min after the dipolarization onset at CCE. It should be mentioned that the onset time of Pi 2 pulsation is sometimes difficult to determine with an accuracy better than 1 min. We defined Pi 2 onset as the starting time of magnetic

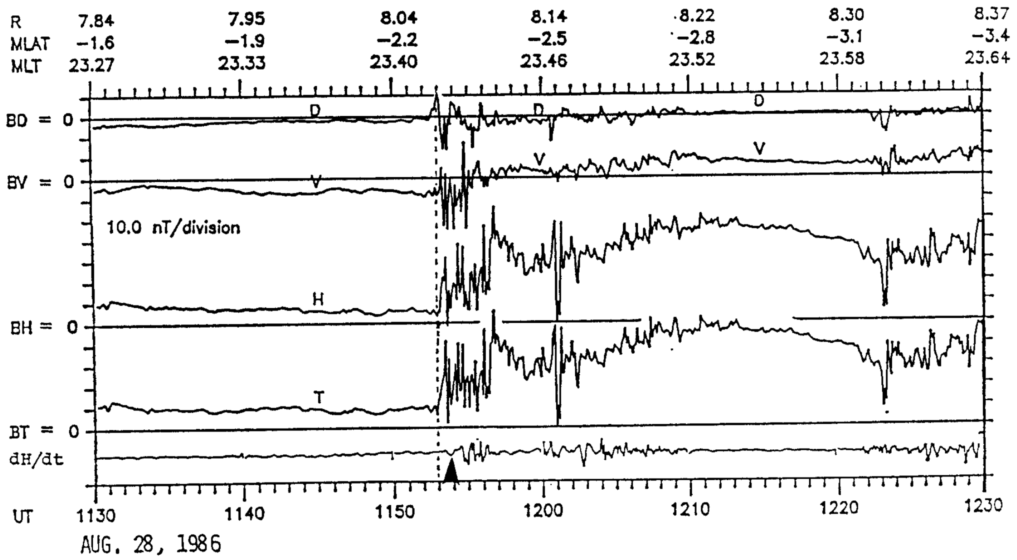

Fig. 1. Amplitude-time records of substorm-associated magnetic variation at AMPTE/CCE and induction magnetogram at low-latitude ground station (ONW) on August 28, 1986. T, H, V, and D are the total field, component antiparallel to the dipole axis, radial (outward) and azimuthal (east) components, respectively. The arrow indicates onsets of dipolarization at CCE and Pi 2 at ONW.

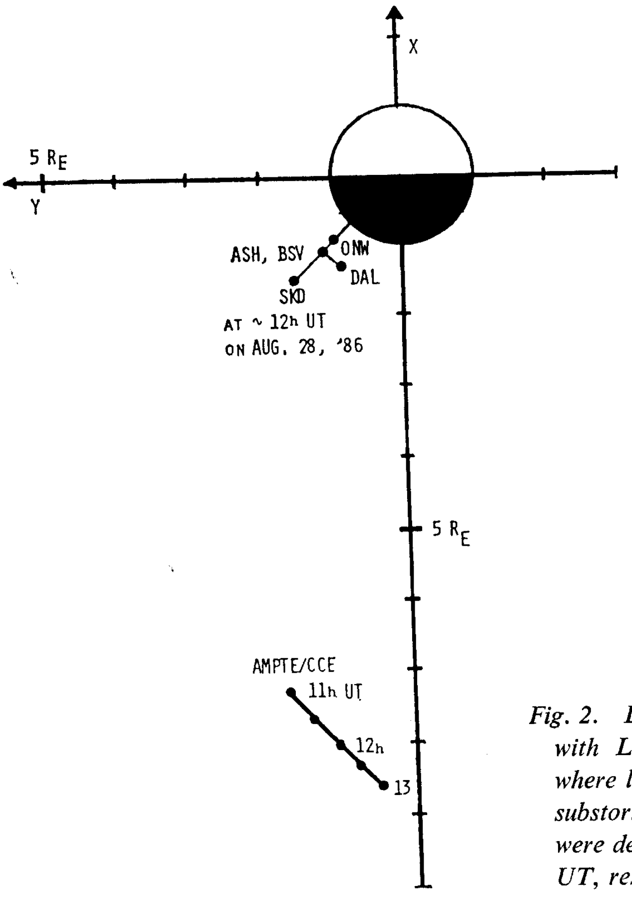

Fig. 2. Locations of conjugate stations with $L=1.3$–2.1 and AMPTE/CCE, where low-latitude Pi 2 pulsations and substorm-associated dipolarization were detected at 1154 UT and at 1153 UT, respectively, on August 28, 1986.

field increase ($dH/dt>0$).

The enlarged magnetic field data from CCE, the low-latitude conjugate stations, and the auroral latitude station College ($\phi=64.86°$, $\lambda=147.84°$) for the substorm event are shown in Fig. 3. The magnetic data from CCE was studied in detail by TAKAHASHI *et al.* (1987) as a case of possible magnetic reconnection event in the near-earth tail. The low-latitude data obtained with rulfmeters (Ring-core fluxgate ULF magnetoMETER) were bandpass filtered for comparison with the induction magnetogram from ONW. The Pi 1–2 activity on the ground started at 1154 UT, approximately 1 min after the onset of "dipolarization process" at CCE which was

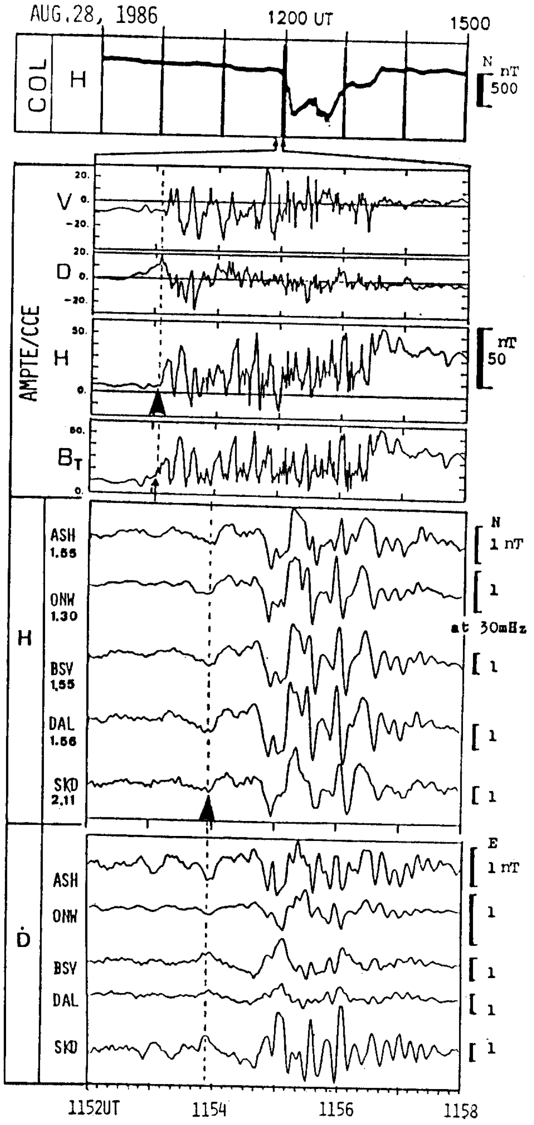

Fig. 3. Enlarged amplitude-time records of August 28, 1986, substorm event. Top, middle and bottom two panels show magnetic fields in the horizontal direction at College, Alaska, in the V (radial), D (azimuthal), H (anti-parallel to geomagnetic axis), and T (total) coordinate at AMPTE/CCE in the midplane of near-earth magnetotail (~8 R_E), and in the north-south and east-west directions in the low-latitude conjugate area, respectively.

located very near the tail current sheet ($\Delta Z = -0.1\ R_E$) near midnight (~23.4 h MLT) at a radial distance of ~8.1 R_E. The time lag of ~60 s can be taken as an indication for the propagation of compressional Pi waves across the ambient magnetic region in the near-earth magnetotail to the low-latitude ground stations, because there is no time delay in between the magnetic signals observed at the satellite location and the reconnection (or disruption) region in this event.

The 1153 UT event was unique because the magnetic field exhibited a persistent ~13 s oscillation during the sequence of dipolarization. The oscillation had a large amplitude in the B_H (approximately equal to B_T) and B_V components, with B_T changing from less than 10 nT to greater than 40 nT. During the oscillation the field turned southward repeatedly. TAKAHASHI *et al.* (1987) suggested that the southward turning was due to the formation of a magnetic neutral line or lines and that the oscillation was caused by a periodic motion of the magnetic field structure. The ground magnetograms for the event also showed a unique variation, because of the excitation of ~13 s *D*-component oscillation.

Before detailing the *D*-component resonance, we describe the field variation which can be attributed to a conventional *H*-component Pi 2. The pulsation can be recognized as a ~34 s variation in the *H*-component with almost identical wave forms at the five low-latitude stations. The ~34 s pulsation is also seen in the *D*-component amplitude-time records at ASH ($L=1.55$) and SKD (2.11). It is noteworthy that the average amplitudes of the *H*-component pulsations at SKD ($L=2.11$), ASH (1.55), BSV (1.55) are comparable to one another. The multi-station data enable us to infer the propagation characteristics of the Pi 2 signal. From a time lag analysis of the *H*-component data, we find that there is a time lag of ~1.5 s from ONW ($L=1.3$) to ASH (1.55) and a lag of ~3 s from BSV (1.55) to SKD (2.11). These observations suggest that the phase front of the *H*-component propagates poleward. Likewise, we can use the longitudinal pair BSV and DAL to determine the azimuthal wave number. The time lag of 1.9 s of the *H*-component signal between these stations yields a westward propagation with an azimuthal wave number of 1.7. This result is consistent with that of YUMOTO (1986), who showed that Pi 2 pulsations at magnetic latitudes lower than 30° propagate westward in the premidnight sector.

An oscillation with ~60 s period is present in the *D*-component, but the wave forms at the northern and southern hemispheres are the mirror image of each other. The ~13 s oscillation can be seen in both *H*- and *D*-components at all latitudes, but in contrast to the *H*-component Pi 2 pulsations, the largest amplitude in the *D*-component is found at the highest latitude (SKD, $L=2.11$). In general, the amplitude decreases steeply with latitude: the *D*-component amplitude at BSV ($L=1.55$) is only 30% of that at SKD. The *D*-component waveforms of the 13 s oscillations from a northern (ASH, $L=1.55$) and a southern (SKD, 2.11) stations on the same magnetic meridian are compared in Fig. 4. The important features of the figure are (1) that the wave frequency is identical at the two conjugate-pair stations, and (2) that the waveforms are almost perfect mirror images of each other. The first point suggests that the oscillation has the same frequency over a range of *L* value, and the second point implies that the oscillations are consistent with an odd mode oscillation of the field lines (*cf.*, SUGIURA and WILSON, 1964). A possible interpretation of the ~13 s wave can be given in terms of field line resonance driven by a quasi-monochromatic source wave (CHEN and HASEGAWA, 1974; SOUTHWOOD, 1974). This theory was developed primarily to prove toroidal-mode standing Alfvén waves observed on the dayside. The ~13 s oscillation on the nightside is also likely to be due to a toroidal-mode standing wave.

It is known that the 90° rotation of the major axis of polarized magnetic wave through the ionosphere (HUGHES and SOUTHWOOD, 1976) is not completed in the presence of horizontal conductivity gradients in the ionosphere (*e.g.*, GLASSMEIER, 1984). Especially, at lower latitudes of $\Phi \lesssim 45°$ (where the height-integrated conductivity ratio Σ_H/Σ_P has a larger gradient in the solar minimum phase and the smaller conductivity ratio in the solar maximum phase (M. TAKEDA, pers. commun.; also see Fig. 7 in Summary and Conclusion) we cannot expect the perfect 90° rotation of the major axis of polarized magnetic wave through the ionosphere.

The possible presence of a quasi-monochromatic source located in the near-earth tail was examined by comparing the dynamic spectra for the SKD data and for the CCE data. The spectra shown in Fig. 5 were calculated with the maximum

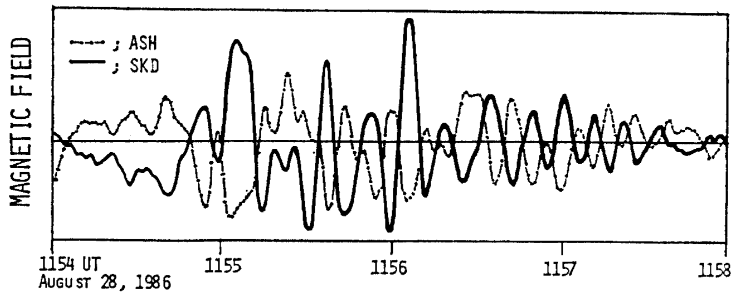

Fig. 4. Phase correlation for the D-component Pi 1 magnetic pulsations observed at low-latitude northern (ASH; broken line) and southern (SKD; solid line) stations during the August 28, 1986, substorm event.

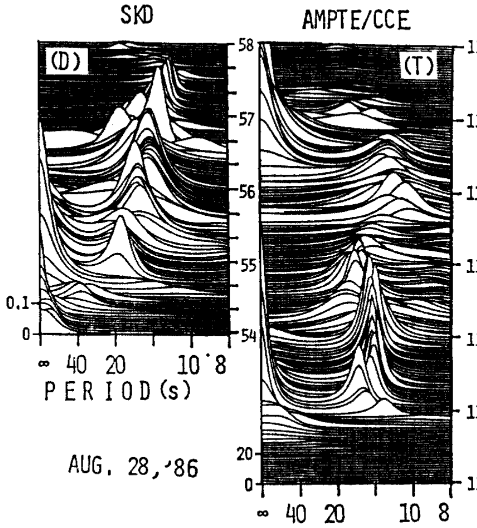

Fig. 5. Dynamic spectrograms of the total field at AMPTE/CCE and the D-component Pi magnetic pulsation at SKD during the August 28, 1986, substorm event. The relative linear scale of power density of the total component at AMPTE/CCE is 200 times that of the D-component at SKD.

entropy method (ULRICH and BISHOP, 1975). A time window of 60 s is shifted by 2 s for successive calculations of the power spectra in the figure. We note here that a compressional wave (period 13–15 s) at CCE started at 1153:10 UT, while the 13–15 s pulsation on the ground started at 1154:20 UT. The time lag of 70 s between the onsets of these waves is comparable to the time lag ~60 s between the dipolarization at CCE to the onset of the Pi pulsation on the ground. The time lag of 70 s over the distance of 7 R_E indicates an average propagation speed of 600 km/s, which is comparable to the Alfvén velocity inside the plasmapause.

4. Summary and Conclusion

From the correlation and the spectral analyses of magnetic field data at conjugate-pair stations around L=1.3–2.1 and the AMPTE/CCE spacecraft for the August 28, 1986 substorm event we found the following relations between low-latitude Pi 1–2 plusations and substorm-associated phenomena at AMPTE/CCE:

1. Low-latitude Pi 1–2 activities started after ~60 s of the onset of the expansion phase determined by CCE (Fig. 3).
2. The phase propagation of the H-component pulsation with ~34 s period was poleward in the meridional plane and westward in the premidnight sector. The phase lag between L=1.3 and 2.1 was ~4.5 s, and the apparent azimuthal wavenumber was $|m|$~1.7.
3. The amplitude of the H-component pulsations was almost independent of latitude, whereas that of the ~13 s oscillation in the D-component varied strongly with latitude.
4. The compressional field oscillation at CCE started ~70 s before the onset of the ~13 s oscillation on the ground.
5. The D-component waveforms at higher latitudes (SKD, ASH) showed the odd-mode standing oscillation with a quasi-monochromatic period of 13–15 s (Figs. 4 and 5).

Figure 6 illustrates a possible scenario for the excitation and propagation mechanisms of Pi pulsations observed at 1154 UT on August 28, 1986. On one hand, an Alfvén wave in the near-earth magnetotail (~8 R_E) is impulsively excited at the onset of the expansion phase of a substorm. This wave propagates along the field line to the high-latitude ionosphere, producing high-latitude Pi 2 pulsation. On the other hand, compressional waves composed of impulse and quasi-monochromatic component are also excited at the onset, propagate across the ambient magnetic field, and reach the inner plasmasphere, where they couple to a cavity resonance-like Pi 2 oscillation and a standing-like Pi 1 oscillation, respectively. The observed phase propagations of the H-component Pi 2 pulsation in the poleward and westward directions may be associated with a propagation direction of the compressional wave as shown in Fig. 6.

Recently, ALLAN *et al.* (1986) demonstrated a possibility that impulsively-stimulated compressional "magnetosphere" cavity resonance can drive a localized toroidal field-line standing oscillation where the frequency of poloidal cavity mode matches an eigen-frequency of the uncoupled torsional oscillation. The observed H-com-

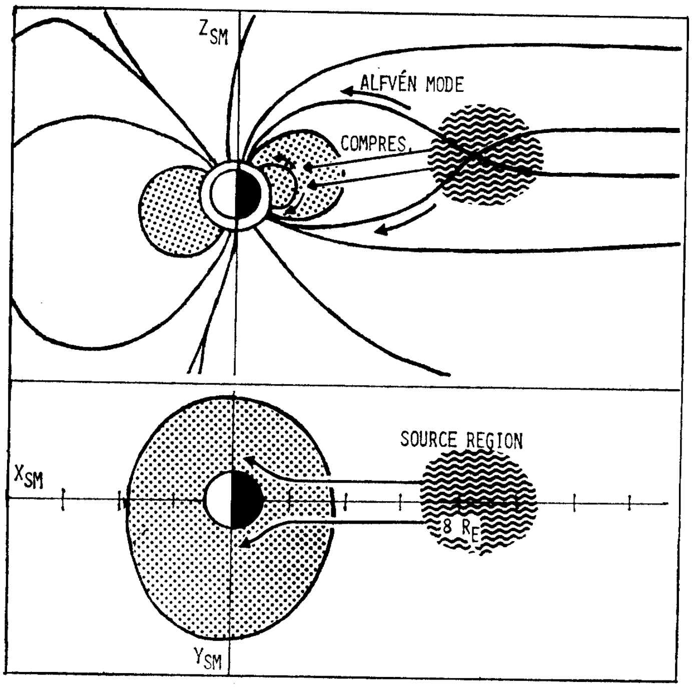

Fig. 6. Schematic illustration for excitation mechanisms of low-latitude Pi 1–2 pulsations observed on August 28, 1986 in the meridian plane (top) and the equatorial plane (bottom). Compressional waves having impulsive and quasi-monochromatic components in the reconnection region (~8 R_E) can propagate across the ambient magnetic field into the nighttime inner plasmasphere, and excite a compressional, poloidal magnetic oscillation (e.g. the poloidal "plasmasphere" cavity resonance) and a guided toroidal field-line oscillation, respectively. They can be coupled further with an H-component pulsation with discrete frequency in a low-latitude wide area and a localized D-component oscillation, respectively, on the ground.

ponent Pi 2 pulsations, with a discrete frequency and comparable amplitudes in a wide area around $L=1.3$–2.1, cannot be explained by a localized toroidal field-line resonance excited by the fundamental "magnetosphere" cavity resonance mode, whereas the D-component Pi 1 pulsation may be due to a localized toroidal standing field-line oscillation excited by the second harmonic cavity mode as predicted by ALLAN *et al.* (1986).

Since the height-integrated ionospheric Pedersen conductivity is larger than that of the Hall conductivity and/or there are larger gradients of the Pedersen and Hall conductivities at lower latitudes on the nightside in the solar minimum phase (Fig. 7 by the courtesy of M. TAKEDA, pers. commun.), the magnetic fields caused by currents flowing in the ionosphere may not be rotated by 90° when they arrive at the ground (see GLASSMEIER, 1984). The H-component Pi 2 pulsations observed on the ground on the nightside can be caused by an ionospheric Pedersen eddy current ($\tilde{J}_p$) induced by inductive electric field ($\nabla \times \tilde{E}_{\mathrm{iono}} = -\partial \tilde{B}_p/\partial t$) of poloidal source wave ($\tilde{B}_p$) (including the impulsively-stimulated poloidal "magnetosphere" cavity resonance mode) in the ionosphere of non-uniform conductivity, as shown in Fig. 8 (*cf.*, YUMOTO *et al.*, 1987). Moreover, the general H-component Pi 2 pulsations, which have the same period and a slowly varying amplitude from $L=1.3$ to 2.1 as the August 28

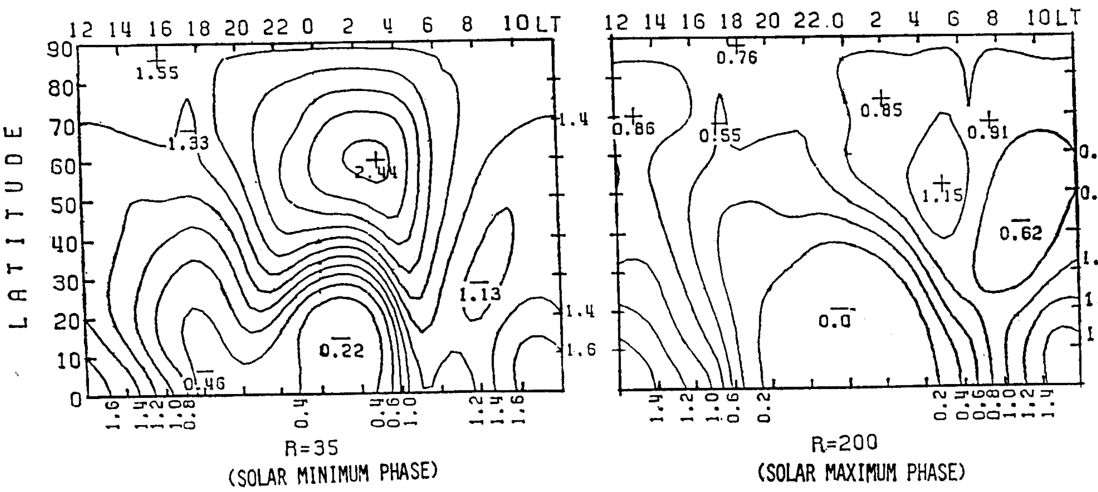

Fig. 7. *Estimated distributions of ratios (Σ_H/Σ_P) of the height-integrated ionospheric Hall to Pedersen conductivity in the solar minimum (left) and maximum (right) phase (by the courtesy of M. TAKEDA).*

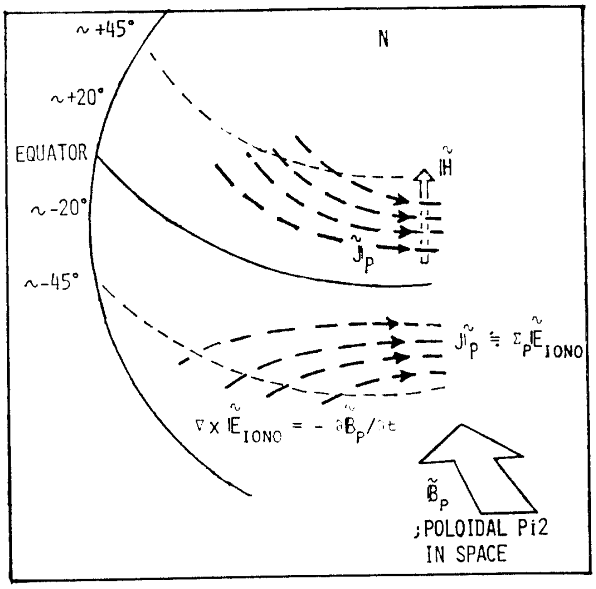

Fig. 8. *Schematic illustration for the generation mechanism of magnetic Pi 2 pulsations at low latitudes on the ground. A compressional, poloidal magnetic wave (and/or oscillation) ($\tilde{B}_P$) excited at the substorm expansion onset in the nighttime magnetosphere can induce an inductive electric field ($\nabla \times \tilde{E}_{\rm iono} = -\partial \tilde{B}_P/\partial t$) in the low-latitude ionosphere. The ionospheric Pedersen current oscillation ($\tilde{J}_P$) caused by the electric field can contribute to magnetic Pi 2 pulsation on the ground.*

event (although not shown in the text), cannot be interpreted as the Alfvén resonance, *i.e.*, toroidal standing oscillation of local field lines with $\lesssim$40 s period at $L \lesssim 2.5$ (*e.g.*, POULTER *et al.*, 1984). The *H*-component Pi 2 and *D*-component Pi 1 pulsations may be associated with poloidal and toroidal oscillations, respectively, above the low-latitude nightside ionosphere. Although we cannot rule out the possibility of the non-90° rotation without numerical studies, the H-component Pi pulsations in the plasmasphere may be also the global eigenmode of Alfvén waves (or discrete Alfvén waves) with $m \neq 0$ near the minimum Alfvén velocity on the Tokamak (*e.g.*, APPERT *et al.*, 1984; COLLINS *et al.*, 1986). Further theoretical and observational studies are required in order to give a full explanation for the generation and wave characteristics of the H-component Pi pulsations at low latitudes ($L \lesssim 2$).

Azimuthal wavenumber of the standing D-component Pi pulsation cannot be determined using the single SKD ($L=2.1$) station data alone, but it is theoretically believed that the guided poloidal and toroidal magnetic waves have a larger and a smaller azimuthal wavenumber, respectively. Although further coordinated east-west chain stations around $L=2.1$ are required to estimate the azimuthal wavenumber and to identify whether the observed Pi 1 magnetic pulsation is a poloidal or a toroidal mode in space, the smaller ionospheric Hall conductivity at nighttime low latitudes suggests that the observed D-component Pi pulsation could be a toroidal standing field-line oscillation in the plasmasphere.

It is very interesting to note that potential evidence was found in the nightside magnetosphere for the couplings between the compressional waves with impulsive and quasi-monochromatic components in space and the H-component Pi 2 and the D-component Pi 1 oscillations on the ground, respectively.

Acknowledgments

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