Evidences of Magnetospheric Cavity Pi 2 Waves

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(Received December 6, 1989; Revised August 9, 1990)

We demonstrate convincing new evidence that Pi 2 magnetic pulsations occur simultaneously in both the nightside and dayside hemispheres, especially at low latitudes. These results allude to the existence of a global cavity mode of Pi 2 pulsations in the inner magnetosphere. However, the direct coincidence between spacecraft-observed and ground-based global Pi 2 events has not yet been sufficiently confirmed.

1. Introduction

At the magnetospheric substorm onset, transient hydromagnetic oscillations, called Pi 2 magnetic pulsations, are excited globally in the magnetosphere (see reviews of BAUMJOHANN and GLASSMEIER, 1984; YUMOTO, 1986, 1988). KATO (1965) first found a correlation between substorm-associated magnetic variations sampled at 5.46 min by the IMP-1 satellite in the magnetotail and Pi 2 magnetic pulsations observed at low latitudes (Onagawa, ONW, $L=1.3$). One possible source of nighttime Pi 2 pulsations is the sudden changes in magnetospheric convection or configuration during the substorm expansive phase (AKASOFU, 1980), which would be caused by a plasma flow from the reconnection (or current disruption) region or by the formation of a substorm current wedge (MCPherron *et al.*, 1973) as shown in Fig. 1(A). Pi 2 polarizations in the midnight sector are believed to be the result of the oscillation of part of the substorm current wedge field-aligned currents (LESTER *et al.*, 1984), whereas high-latitude Pi 2 pulsations on the nightside are generally considered to be a transiently-excited oscillation of the auroral field lines (BAUMJOHANN and GLASSMEIER, 1984; YUMOTO, 1986, 1988) (see Fig. 1(B)). The higher-latitude wave characteristics of Pi 2's were explained by using the odd mode standing oscillation guided along an auroral field line (SUGIURA and WILSON, 1964). However, the excitation and propagation mechanisms of global Pi 2's observed at various longitudes and latitudes still remain open questions.

2. Evidences of Global Pi 2's

Ground Pi 2 magnetic pulsations have the common wave characteristics of global modes observed at various latitudes and longitudes on the night and dayside (see YUMOTO, 1986). Figure 2 shows examples of global Pi 2 events simultaneously detected on the dayside at high (Syowa, SYW; $L=6.15$, Husafell, HSF; $L=5.98$, $MLT \approx UT$) and low latitudes (Hermanus, HER; $L=1.88$, $MLT \approx UT+0.3$ hr) and on the nightside at low latitudes (ONW; $L=1.3$, $MLT \approx UT+9.0$ hr). The arrows indicate substorm-associated Pi 2 onsets determined by the ONW induction magnetogram. The H components of low-latitude Pi 2's on the 3rd and 30th of August 1986 are found to show a nearly in-phase

Fig. 1. (A) Substorm current wedge model during the substorm expansive phase. (B) High-latitude Pi 2's model on the nightside; a transient auroral field-line oscillation in the nightside auroral zone, excited by sudden changes in the magnetotail.

relationship between HER on the dayside southern hemisphere and ONW on the nightside northern hemisphere. It is noteworthy that even though Pc 3 magnetic pulsations, originating from upstream waves in the earth's foreshock (cf. review paper by YUMOTO, 1988), are activated during local daytime, the amplitude-time records at HER after having been passed through a Pi 2 frequency-range filter show corresponding clear transient daytime oscillations.

However, the identification of daytime Pi 2's by using this filter sometimes remains uncertain if prior pulsations had a Pc 4-range frequency. By using the new adaptive filter of the CDANC (Correlated Data Adaptive Noise Canceling) method (HATTINGH, 1988), SUTCLIFFE and YUMOTO (1990) further checked statistically to see if Pi 2's occur during local daytimes at ONW and HER during the 82 events which were selected during local nighttimes at HER and ONW, respectively, from August 3 to September 4, 1986. Figure 3 shows one example of amplitude-time records obtained concurrently on the dayside at HER and on the nightside at ONW, and Pi 2 and Pc 3 components at HER after having been passed through the adaptive filter of the CDANC method (the lower panel). Pi 2 onsets are identified by the ONW induction magnetogram. Even though Pc 3 magnetic pulsations were activated during the local daytime at HER (see the top panel of Fig. 3) and buried the substorm-associated Pi 2 components in the sinusoidal magnetic

Fig. 2. *H*-component induction magnetograms of global Pi 2 events observed on the dayside at high (SYW and HSF) and at low latitudes (HER) and on the nightside at low latitudes (ONW). The arrows indicate low-latitude Pi 2 onsets identified at ONW on the nightside. The negative and positive *H* axes at HER and ONW, respectively, are directed towards the north.

variations, the amplitude-time records at HER through the CDANC filter show clearly corresponding daytime Pi 2 waves (cf. SUTCLIFFE and YUMOTO, 1989). They found that most ($\geq 90\%$) of the corresponding daytime Pi 2's could be identified at low latitudes. They also confirmed that at mid latitudes, daytime Pi 2's are sometimes not detected. Differences in Pc 3 frequency at two South-Africa stations separated by $\sim 35^\circ$ in longitude were ascribed to differences in plasma density affecting the field line resonance frequency; however, the Pi 2's at these two stations have similar power spectra. These findings point to a global cavity mode as the source of low-latitude Pi 2 magnetic pulsations.

Recently, in order to investigate the generation mechanism of global Pi 2 pulsations, YUMOTO *et al.* (1989) have carried out multiple ground-based and satellite observations with high-time resolution data ($\Delta t = 1$ sec). An event which occurred at 11:53 UT on August 28, 1986, was found to exhibit a unique wave form both in space and on the ground. Figure 4 shows the magnetic fields at the auroral latitude station College, Alaska (geographic latitude; $\lambda = 64.86^\circ$, geographic longitude; $\phi = 212.17^\circ$, $L = 5.64$), at AMPTE/CCE (23.4 MLT, -2.2° MLT, $R \sim 8.1 R_E$) in the magnetotail and at the Japan-Australia low-latitude conjugate stations (ASH; geographic latitude $\lambda = 43.97^\circ$, geographic longitude $\phi = 142.20^\circ$, $L = 1.55$, ONW; 38.43° , 141.48° , 1.30 , BSV; -25.83° ,

Fig. 3. Simultaneous amplitude-time records on the dayside (HER) and on the nightside (ONW). Arrows indicate Pi 2 onsets at ONW in local nighttime. Lower two variations show daytime Pi 2 and Pc 3 components at HER, obtained by passing through the CDANC filtering method.

139.3°, 1.55, DAL; -27.18°, 151.20°, 1.56, SKD; -34.70°, 138.50°, 2.11). As the arrows indicate, the ground Pi 2 magnetic pulsations started at ~11:54 UT, ~1 min after the onset of the “dipolarization”, i.e. the step-like variation (YUMOTO and TAKAHASHI, 1989) in the H -component (anti-parallel to the earth’s dipole axis) magnetic field was observed by the AMPTE/CCE spacecraft located very near the center of the tail current sheet. The southward turning ($H < 0$) was due to magnetic reconnection (or current disruption during the substorm expansion phase). The 13–15 s oscillation superimposed on the dipolarization was caused by a periodic motion of the neutral line or lines (TAKAHASHI *et al.*, 1987). The ~1-min time lag of the onsets corresponds to a propagation time of transient signals from space to ground. It is also noteworthy that the ~13 s compressional oscillation in the total magnetic field at AMPTE/CCE started at ~11:53:10 UT, while a pulsation on the ground with an almost identical period, especially appearing in the D component, started ~70 s later at 11:54:20 UT. Both in space and on the ground, the oscillations lasted for ~3 min. The concurrent occurrence of ~13 s oscillations in space and on the ground leads us to speculate on the causal relationship between the two. The time lag of ~70 s between the onsets of these waves is comparable to the time lag of ~60 s between the starting time of “dipolarization” at the AMPTE/CCE and the onset of Pi 2 pulsations on the ground. The time lag of ~60 s over the distance of 7 R_E translates into an average velocity of ~750 km/s, which is of the same order as the averaged Alfvén velocity in the inner magnetosphere.

We can interpret that hydromagnetic disturbances are launched at the time of field dipolarization in the reconnection (or current disruption) region in the near-earth tail during the substorm expansive phase (AKASOFU, 1980). The compressional portions of

Fig. 4. Amplitude-time magnetic records of the August 28, 1986, substorm event. (Top) H -component variation at College, (Middle) V (radial), D (azimuthal), H (anti-parallel to geomagnetic axis), T (total) components at AMPTE/CCE in the magnetotail ($\sim 8 R_E$), and (Bottom) H and D components of time-derivative magnetograms in the low-latitude conjugate area at $L=1.3-2.1$ (see YUMOTO *et al.*, 1989). The right, lower-side scale indicates the sensitivity for pulsations with a 30 mHz frequency.

hydromagnetic disturbances at AMPTE/CCE are believed to propagate across the equatorial magnetic field and to couple into a global Pi 2 and a localized Pi 1 magnetic pulsation, respectively, on the ground.

YUMOTO *et al.* (1990b) also investigated the wave characteristics of global Pi 2 magnetic pulsations detected concurrently on the ground at world-widely separated stations (SYW; $L=6.15$, $\Lambda=71.44^\circ$, $MLT \approx UT$, HER; 1.88 , 81.52° , $UT+0.3$ hr, Kakioka, KAK; 1.23 , 210.95° , $UT+9.0$ hr) and in space at AMPTE/CCE. Figure 5 shows a global Pi 2 event excited at 23:10 UT on May 22, 1985. From the inspection of hot electron data from the HPCE (hot-plasma composition experiment) instrument on board AMPTE/CCE, the spacecraft entered the plasma sheet at $L \sim 7.1$ at $\sim 23:50$ UT on May 22, 1985 (D. M. Klumpar, private communication). The position of AMPTE/CCE at $\sim 23:10$ UT was located in the plasma trough at $L=6.4$ and 22.8 MLT, i.e. near the Syowa-Iceland conjugate area.

The ground data from the SYW, HER and KAK stations provide the evidence for a "global mode" nature of Pi 2 pulsations. The H -component of Pi 2 pulsations in the nightside hemisphere show a nearly anti-phase relationship between high- and low-latitude ground stations, while D components show a nearly in-phase relationship between SYW and HER (see the lower panel of Fig. 5). On the other hand, both the H - and D -component of Pi 2 pulsations at low latitudes indicate in-phase relationships between HER on the nightside southern hemisphere and KAK on the dayside northern hemisphere. These phase relationships, especially at low latitudes on the dayside, can not be explained by considering either the equivalent ionospheric current system of the magnetospheric substorm (cf. KAMIDE, 1988) or the substorm current wedge model on the nightside (MCPHERRON *et al.*, 1973).

It is also noteworthy that the dominant periods (~ 135 s) of global Pi 2 pulsations

Fig. 5. Amplitude-time magnetic records of the 23:10 UT, May 22, 1985, global Pi 2 event in the plasma trough at AMPTE/CCE and on the ground at high (SYW) and low latitudes (HER) on the nightside and at low latitudes (KAK) on the dayside (see YUMOTO *et al.*, 1990b).

before 23:17 UT on the ground at world-widely separated stations, from $L=1.2$ to 6.9 on the night and dayside, respectively, and of transverse components in the plasma trough at AMPTE/CCE are almost the same. On the other hand, from the analytical solutions, SPEZIALE and CATTO (1977) and KIVELSON and SOUTHWOOD (1986) derived an implicit equation for the eigen frequency of the magnetospheric cavity wave:

$$\omega = V_A(L) * [(3\pi/4)^{2/3} \alpha^{4/3} + (m/LR_E)^2 + k_{\parallel}^2]^{1/2} \quad (1)$$

with $\alpha^2 = \omega^2 \mu_1 / [V_A^2(1) * (L-1)R_E]$. ω , m , $k_{\parallel}$, $V_A(L)$ and $V_A(1)$ are the wave frequency, wave numbers in the azimuthal and parallel directions, the Alfvén velocities at a rigid boundary, i.e. the turning point at L and at the equatorial ionosphere, respectively. The coefficient μ_1 corresponds to the averaged radial dependence of the ambient magnetic field and plasma density. The eigen frequency of a transversely propagating wave, i.e. $(3\pi/4)^{2/3} \alpha^{4/3} \gg (m/LR_E)^2 + k_{\parallel}^2$, can be given approximately as follows:

$$\omega \sim V_A^3(L) * (3\pi/4) \mu_1 / [V_A^2(1) * (L-1)R_E]. \quad (2)$$

For the boundary of $L=7$, $V_A(L)=1000$ km/s, $V_A(1)=4000$ km/s and $\mu_1=10-15$, we have the expected eigen period of 150–100 s, which is in agreement with the observed dominant period of Pi 2's before 23:17 UT as shown in Fig. 5.

Before $\sim 23:17$ UT, one finds good in-phase relationships between B_x (radial out) in space and the D component at SYW and between B_y (eastward) and the H component, suggesting an ionospheric 90° rotation of the transverse wave polarization axis. After $\sim 23:17$ UT, a localized compressional oscillation (B_z) with a 140-s period appeared near the magnetic equator at AMPTE/CCE in spite of ground variations decreasing at the time. Satellite data showing abrupt changes from a predominant transverse to a compressional component and of dominant period present a real conundrum for interpretation.

The cavity resonance wave (cf. KIVELSON *et al.*, 1984; ALLAN *et al.*, 1986; or “trapped oscillation”, YUMOTO and SAITO, 1983) can be excited by sudden changes in the magnetospheric convection or configuration caused by a plasma flow due to magnetospheric reconnection or by a tail current disruption during the substorm expansion phase. However, magnetic perturbations of the cavity resonance wave component (δB_{radial} , $\delta B_{\parallel}$) would be difficult to detect directly in the existing spaceborne magnetometer data set. The possibly stored energy rate $([V_c \times \delta B_{\parallel}^2 / 2\mu] / T \sim 2 \times 10^{15}$ erg/sec, where V_c , $\delta B_{\parallel}$ and T are volume of space, averaged amplitude and period of compressional wave, respectively) of the cavity resonance wave must be of the same order as the total wave power in the solar-wind surface waves (see JUNGINGER, 1985) but less than the energy transfer rate ($\sim 10^{17}$ erg/sec) by the solar-wind magnetosphere coupling (AKASOFU, 1980). The averaged amplitude of the cavity mode with $T \sim 150$ s should be only $\delta B_{\parallel} \sim 0.6$ nT in the inner magnetosphere ($L \leq 7$). Therefore, it is believed that the compressional oscillation with a ~ 140 s period and a ~ 3.5 nT peak-to-peak amplitude at AMPTE/CCE after $\sim 23:17$ UT, as shown in Fig. 5, was not associated with the cavity resonance wave, but was instead associated with a localized compressional oscillation in space (see SAKURAI *et al.*, 1990). The direct coincidence between spacecraft-observed and ground-based global Pi 2 events has not yet been sufficiently confirmed.

3. Discussion

The wave characteristics of global Pi 2 pulsations detected at world-widely separated stations can be summarized as follows: (1) the high occurrence probability of daytime Pi 2's at low and middle latitudes (Figs. 2 and 3), (2) the almost identical period in the inner region ($L \leq 7$) bounded by the plasma sheet (Fig. 5), and (3) the anti- and in-phase relationships between H and D components of global Pi 2's observed at high and low latitudes in the night time and at low latitudes in the daytime sector (see Fig. 5). These characteristics cannot be interpreted by only considering the Alfvén field-line resonance wave (CHEN and HASEGAWA, 1974; SOUTHWOOD, 1974) localized in the nightside auroral zone, but suggest a global field-line oscillation coupled with the magnetospheric cavity resonance wave (see YUMOTO *et al.*, 1990a).

The conclusion obtained from these globally coordinated observations is schematically summarized in Fig. 6, illustrating the possible scenario for the excitation and propagation mechanisms of the substorm-associated global Pi 2 magnetic pulsations. At the substorm expansion onset, hydromagnetic impulsive disturbances are launched at the time of field dipolarization in the reconnection or current disruption region (solid area) in the near-earth plasma sheet. A portion of the disturbances can propagate along the field line in the Alfvén mode to the high-latitude ionosphere and contribute to a localized high-latitude Pi 2 pulsation on the nightside as shown in Fig. 1(B). On the other hand,

Fig. 6. Schematic illustration of the substorm-associated magnetospheric cavity resonance model in the meridional plane. Compressional impulsive waves in the source region (solid area) propagate across the ambient magnetic field into the dayside magnetosphere and excite the magnetospheric cavity resonance wave coupled with a globally forced field-line oscillation with a discrete frequency in the inner magnetosphere. PS, RB, V_r and B_T indicate the plasmasphere, the radiation belt, the radial plasma velocity of cavity mode wave, and the total magnetic field, respectively. The lower left-side figure shows expected amplitude profiles (V_r) of an excited cavity wave as a function of radial distance. The lower right-side figure shows a typical example of step-like magnetic variation in the magnetotail during the magnetospheric substorm expansion phase.

compressional impulsive signals with a broad-band frequency can propagate across the ambient magnetic field into the dayside magnetosphere and excite the cavity resonance mode in the whole inner region (indicated by a thick line in Fig. 6) surrounded by the plasma sheet plasma (a left-handed oblique line). The magnetospheric cavity resonance wave must couple further into a globally forced field-line oscillation with a discrete frequency in inhomogeneous magnetospheric plasmas, which can be observed as a global Pi 2 pulsation at world-widely separated ground stations.

However, the existing spaceborne magnetometer, having a ~ 0.3 nT rms noise level, may not be able to detect the cavity wave component with an amplitude ($\delta B_{\parallel}$) of only ~ 0.6 nT in the inner magnetosphere for the expected value of stored energy rate ($V_c \cdot \delta B_{\parallel}^2 / \mu T \sim 2 \times 10^{15}$ erg/sec) of the magnetospheric cavity wave (YUMOTO *et al.*, 1990b). Although many observational arguments for the occurrence of Pi 2 pulsations in space have been put forward, final observational confirmations from satellite data are still lacking. In addition, the Pi 2 wave propagation in inhomogeneous plasmas still remains an open question. We do not fully understand how Pi 2 waves generated by a localized source are transported in whole magnetospheric plasmas and coupled with the magnetospheric cavity wave. Future computer simulation studies on MHD waves in the realistic, inhomogeneous magnetosphere model and globally coordinated multiple ground-based and satellite observations will establish the global field-line oscillation coupled with the magnetospheric cavity resonance wave in the inner magnetosphere.

Especially, the in-phase relationship of H components between HER on the nightside southern hemisphere and KAK on the dayside northern hemisphere, as shown in Fig. 5, suggests that the H components of low-latitude global Pi 2 waves have an azimuthal wave number of $m \sim 0$ or $m \sim 2$. If the ionospheric 90° rotation of the transverse wave polarization axis could occur at low latitudes, the in-phase relationship of D components between HER and KAK would indicate an azimuthal wave number of $m \sim 1$. In order to establish the longitudinal phase relationships of global Pi 2 pulsations, however, further globally coordinated, longitudinal chain observations at lower latitudes are needed to examine whether the azimuthal wave number of the H (D) component of Pi 2's is ~ 0 or ~ 2 (~ 1). Moreover, theoretical works are also required to investigate if a coupled oscillation of the H component with $m \sim 0$ (or $m \sim 2$) and the D component with $m \sim 1$ could exist as a cavity mode wave in the realistic magnetosphere.

The author expresses his sincere thanks to Profs. Y. Kato, T. Tamao, Drs. K. Takahashi, T. Sakurai, P. R. Sutcliffe, M. Kuwashima, and N. Sato for their suggestive comments on this investigation and for magnetometer data from Hermanus, Kakioka and Syowa-Iceland stations.

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