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Pi2 pulsations observed from the Akebono satellite in the plasmasphere

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Abstract. Magnetic field, electric field, and electron density measurements from the Akebono satellite are used to study the properties of two Pi2 pulsations that occurred in succession on February 13, 1990, when the satellite was in the plasmasphere at $L = 2.4$-3.8, 24°-40° magnetic latitude, and 22.5 hours magnetic local time. Magnetic pulsations with a nearly identical waveform were observed in the same time interval at three ground stations (Aedey, $L \approx 6.84$; York, $L \approx 2.55$; and Hermanus, $L \approx 1.83$), which were located near midnight, confirming that the pulsations propagated to the ground. At the satellite the pulsations had comparable radial and azimuthal components in both the magnetic and electric fields. In contrast to the observations near the magnetic equator by the Active Magnetospheric Particle Tracer Explorers Charge Composition Explorer spacecraft [*Takahashi et al.*, 1995], no compressional component was detected in the magnetic field. The orthogonal components of the electric and magnetic fields oscillated either in phase or 180° out of phase, a property of a propagating (rather than standing) wave. The Poynting flux of the Pi2 pulsations was parallel to the ambient magnetic field and directed toward the nearer ionosphere, with little indication of ionospheric reflection. This unidirectional flow of electromagnetic energy is consistent with the strong ionospheric damping of Alfvén waves estimated from a numerical calculation. It is significant that the measured Poynting flux could damp a cavity mode oscillation in ~10 s, assuming that the previously reported equatorial compressional Pi2 pulsations represent the cavity mode. Since the transverse Pi2 pulsations at Akebono lasted ~400 s, they cannot be due to a gradual energy leakage from a simple cavity mode oscillation. Consequently, if the observed energy flow is a general property of plasmaspheric Pi2 pulsations, a simple cavity mode oscillation excited by an impulsive source is not an appropriate model for Pi2 pulsations.

1. Introduction

Pi2 pulsations are damped oscillations of the geomagnetic field in the period range of 40 to 150 s [*Saito*, 1969]. A Pi2 pulsation usually occurs at the onset of a magnetospheric substorm, which makes it a useful indicator of the onset of substorms [e.g., *Saito et al.*, 1976; *Yeoman et al.*, 1994]. Pi2 pulsations are considered to be excited by hydromagnetic momentum released when the near-Earth ($R \leq 10\ R_E$, where R is geocentric distance and R_E is Earth radius) magnetotail goes through a rapid configurational change at the expansion phase onset of a substorm [*Southwood and Stuart*, 1980]. However, it is not fully understood how the impulsive change in the near-Earth tail produces Pi2 pulsations, especially those in the inner ($L < 5$) magnetosphere, which exhibit a well-defined period and a high degree of coherence over many hours of local time and many degrees of latitude. In this paper we use a unique data set from the Akebono satellite to investigate the oscillation mode and exciting mechanism of Pi2 pulsations in the inner magnetosphere.

The paper is organized as follows. Section 2 summarizes previous observations and models of Pi2 pulsations. Section 3 describes the Akebono satellite and ground stations used in this study, and section 4 examines two Pi2 events observed by the satellite. Section 5 discusses the Pi2 events in relation to the previous Active Magnetospheric Particle Tracer Explorers Charge Composition Explorer (hereafter referred to as CCE) results by *Takahashi et al.* [1995] and also in relation to the Pi2 models. Section 6 gives the conclusions.

2. Review of Previous Studies

In this section we review previous ground and satellite observations as well as Pi2 models proposed from the studies. In section 5 the models are subjected to a critical examination in light of Akebono observations.

2.1. Ground-Based Observations and Pi2 Models

Various models have been proposed for Pi2 at $L < 5$, primarily based on ground-based observations, as briefly reviewed here.

2.1.1. Surface waves on the plasmapause. *Chen and Hasegawa* [1974b] presented a theory of surface waves on a boundary across which the Alfvén speed changes rapidly. The

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frequency of the surface waves is determined by the Alfvén velocities on the two sides of the boundary, and the frequency can be in the Pi2 band if the surface waves are excited on the plasmapause. *Sutcliffe* [1975] found harmonically related peaks in Pi2 spectra and suggested that they originate from surface waves on the plasmapause. *Lester and Orr* [1983], using magnetometer data from two magnetometer arrays (one located from $L = 2.5$ to 6.7, and the other located from $L = 3.3$ to 6.2) and plasma density data from the GEOS 1 and ISEE 1 satellites, argued that surface waves on the plasmapause play a dominant role in determining the Pi2 properties at midlatitudes. *Southwood and Stuart* [1980] reviewed theory and observation of Pi2 and suggested that midlatitude Pi2 is due to a surface wave traveling along the plasmapause.

2.1.2. Shear Alfvén mode resonances. Distant source waves can couple to local shear Alfvén waves through the field line resonance mechanism [*Chen and Hasegawa*, 1974a; *Southwood*, 1974]. One manifestation of the resonance is the latitudinal reversal in the polarization of field perturbations, which can be observed by magnetometer arrays. *Fukunishi* [1975] analyzed magnetic field data covering $L = 3.2$ to 4.4 and demonstrated that the H components of Pi2 pulsations are in phase between northern and southern conjugate stations, while the D components are out of phase. In addition, Fukunishi observed a latitudinal ~180° phase shift in H near $L = 4$. Consequently, he argued that Pi2 pulsations near $L = 4$ are an odd mode standing Alfvén wave that is in resonance with a high-latitude source wave. *Stuart et al.* [1979] analyzed the polarization of Pi2 recorded at a latitudinal magnetometer array from $L = 2.4$ to $L = 3.8$ and concluded that the spatial variation of the polarization was consistent with the field line resonance mechanism as illustrated by *Hughes and Southwood* [1976].

2.1.3. Cavity mode resonance. Compressional (fast mode) magnetohydrodynamic waves may establish a cavity mode oscillation in the magnetosphere if appropriate boundary conditions exist. The cavity resonance model for the midlatitude and low-latitude Pi2 was first suggested by *Saito and Matsushita* [1968] on the basis of the analysis of more than 6000 Pi2 events identified in rapid-run magnetograms from Onagawa ($L \approx 1.32$) and Fredericksburg ($L \approx 2.37$). The key signature of the cavity mode is the large spatial extent of the oscillating magnetic field. *Stuart* [1974] suggested that the secondary amplitude maximum of Pi2 occurring between $L = 2.5$ and $L = 4$ is due to a plasmaspheric cavity resonance. Using the British Geological Survey magnetometer array ($L = 2.38$-6.23 [*Stuart*, 1982]), *Yeoman and Orr* [1989] concluded that plasmaspheric cavity resonance is the most likely mechanism for the secondary amplitude maximum of midlatitude Pi2. In a related study, *Yeoman et al.* [1990a, 1991] concluded that Pi2 pulsations consist of an auroral zone Alfvén wave and a lower-latitude compressional wave which might be a cavity mode wave. From observations of dayside low-latitude Pi2 pulsations, *Sutcliffe and Yumoto* [1989, 1991] also concluded that low-latitude Pi2 pulsations are a consequence of the cavity mode. Mathematically rigorous analyses of the cavity mode have been presented by a number of authors [*Kivelson and Southwood*, 1986; *Southwood and Kivelson*, 1986; *Zhu and Kivelson*, 1989; *Allan et al.*, 1986a, 1986b; *Lin et al.*, 1991; *Lee*, 1996].

2.1.4. Oscillating current wedge. The baseline variation of the magnetic field in the near-Earth magnetotail during a substorm can be explained by the formation of a current wedge; a secondary oscillating current flowing on the same current circuit has been suggested as the source of Pi2 pulsations. *Lester et al.* [1983, 1984, 1989] examined the relationship between Pi2 polarization and the location of the substorm current wedge. They showed that the orientation of the major axis of polarization is directed toward the center of the current wedge. Satellite observations in support of the current wedge source have been reported. *Sakurai and McPherron* [1983], who examined magnetic field data from the synchronous ATS 6 satellite, found that Pi2 pulsations can be classified into three types: 100-s irregular oscillations accompanied by high-frequency oscillations; 100-s irregular oscillations without high-frequency oscillations; and east-west transverse oscillations. The first two types have a significant compressional component, whereas the third type is purely transverse. Sakurai and McPherron found that the initial Pi2 perturbation in the azimuthal component has the same sign as the initial perturbation arising from the main field-aligned current of the substorm current wedge. The authors concluded that Pi2 pulsations are caused by an oscillating current flowing on the current wedge.

2.2. Status of Satellite Observations

Only satellites can directly measure the state of the ambient plasma and the perturbations in the electric and magnetic field associated with Pi2 pulsations. Satellite observations can distinguish between compressional and transverse waves and between propagating and standing waves. Furthermore, multisatellite case studies or single-spacecraft statistical analyses of the amplitude and phase allow the mode structures of Pi2 pulsations to be determined. Once these wave properties are known, some Pi2 models can be eliminated. For example, field line resonance and surface waves are radially localized transverse oscillations, whereas cavity mode waves are compressional waves extended radially.

Until now, satellite observations have provided limited information on the Pi2 mode. Early geosynchronous observations [e.g., *Sakurai and McPherron*, 1983] could not directly address the questions regarding Pi2 pulsations in the inner ($L < 5$) magnetosphere. Using GEOS 2 electric and magnetic field data, *Yeoman et al.* [1990b] reported that the energy flow at the substorm onset at geosynchronous orbit showed a remarkable lack of the field aligned component. They also showed for an event that the characteristic perturbation at the satellite was quite different from that observed at the midlatitude ground stations ($L = 2.59$-3.65). In a recent study using magnetometer data from the CCE spacecraft that covered $L = 2$-7 and magnetometer data from a ground station located at $L \approx 1.2$, *Takahashi et al.* [1995] showed that at CCE, pulsations exhibiting high coherence with ground Pi2 were detected only on the nightside and primarily at $L < 5$. Within the CCE magnetic latitude (λ_m) range of ±16°, Pi2 pulsations were characterized as compressional poloidal-type oscillations, with radial amplitude and phase structures suggesting a cavity mode resonance. Having no electric field or plasma density measurements from CCE, Takahashi et al. could not unambiguously determine the oscillation mode of Pi2. No observation of Pi2 pulsation in the higher latitude ($\lambda_m > 16°$) portion of the inner magnetosphere has been reported to the authors' knowledge.

In this study we analyze Pi2 pulsations observed from the Akebono satellite on a pass within the plasmasphere.

Table 1. Station Locations

		Geographic Coordinates, deg		Geomagnetic Coordinates, deg			Magnetic Local Time, hours
Station Name	Abbreviation	Latitude	Longitude	Latitude	Longitude	*L*	
Aedey	AED	66.09°	335.35°	67.53°	68.77°	6.84	22.25
York	YOR	53.95°	358.95°	51.20°	79.10°	2.55	22.94
Hermanus	HER	-34.42°	19.23°	-42.42°	81.93°	1.83	23.13

Geomagnetic coordinates, *L* values, and magnetic local time (at 2250 UT) are calculated on the basis of the International Geomagnetic Reference Field 1990 model at a 100-km altitude.

Measurements of the magnetic field, electric field, and plasma density available from the satellite make it possible to discuss the local propagation mode of the pulsations as well as the electromagnetic energy flow associated with the pulsations. We also use ground magnetometer data to discuss the global propagation properties of the pulsations.

3. Experiments

The satellite and ground experiments used for this study are briefly described in this section.

3.1. Akebono Experiments

The Akebono satellite was launched on February 22, 1989, into a semipolar orbit with an apogee of 10,500 km (altitude), a perigee of 274 km, an inclination of 75°, an orbital period of 212 min, and a spin period of ~8 s [*Oya and Tsuruda*, 1990]. The spin axis of the satellite points to the Sun. In this study we use data from three experiments conducted on board the satellite: the double-probe electric field detector (EFD-p) [*Hayakawa et al.*, 1990], the fluxgate magnetic field detector (MGF) [*Fukunishi et al.*, 1990], and the plasma wave detectors in high-frequency range and sounder (PWS) [*Oya et al.*, 1990]. The EFD-p experiment measures electric fields only in the satellite spin plane, so the assumption of zero electric field along the magnetic field is used to derive three-component electric field vectors. We use spin-averaged (~8-s) data from EFD-p and MGF, and 32-s averaged data from the plasma wave experiment.

3.2. Ground Magnetometers

We compared the Akebono data with data from three ground magnetometer stations. The stations are Aedey (AED), operated by the National Institute of Polar Research, Japan; York (YOR), which is part of the U.K. Subauroral Magnetometer Network (SAMNET) magnetometer stations [*Yeoman et al.*, 1990a]; and the Hermanus (HER), operated by Hermanus Magnetic Observatory [*Sutcliffe and Yumoto*, 1989]. The coordinates of these stations are listed in Table 1. AED and SAMNET provide fluxgate magnetometer data, while HER provides induction magnetometer data. Hence the original time derivative time series from HER, *dH*/*dt* and *dD*/*dt*, were converted to *H* and *D* using an experimentally determined frequency response function of the magnetometer.

4. Data

The Pi2 events studied in this paper occurred at 2242 and 2251 UT on February 13, 1990. Figure 1 shows the magnetic field records from the three ground stations for a 2-hour interval spanning the Pi2 pulsations which we call A and B, as indicated above the York *D* trace. As Table 1 shows, the stations were located near 22 hours magnetic local time (MLT) but were widely separated in latitude. All the ground data indicate a substorm onset at ~2240 UT, coincident with the onset of Pi2

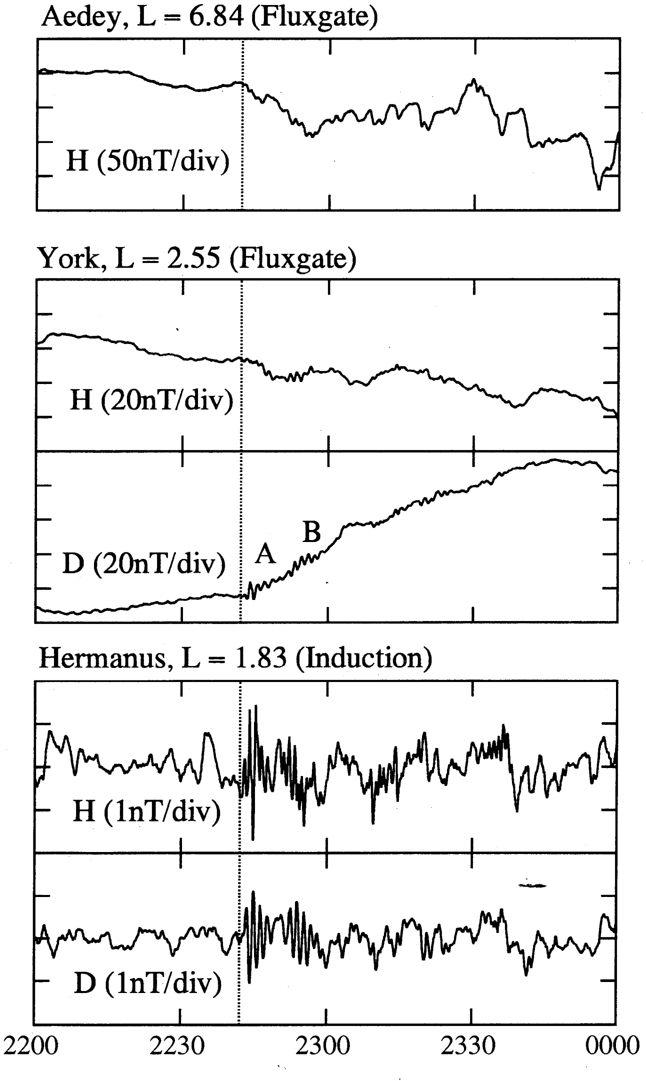


Figure 1. Magnetic field records from Aedey (geographic coordinates 66.09°N, 22.65°W, *L* = 6.84), York (53.95°N, 358.95°E, *L* = 2.55), and Hermanus (34.42°S, 19.23°E, *L* = 1.83) recorded on February 13 (Day 44), 1990. The Hermanus data were constructed from induction magnetometer data using an empirically derived magnetometer frequency response function. The vertical line indicates the onset time of a substorm as identified from Pi2 onset at Hermanus. Pi2 pulsations started at 2242 and 2251 UT.

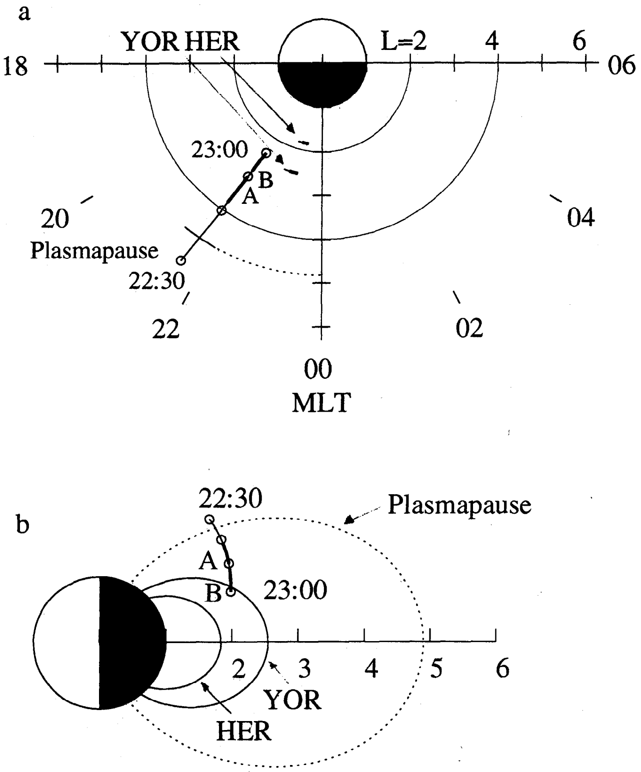


Figure 2. The orbit of the Akebono satellite on February 13, 1990, for a 30-min interval spanning Pi2 pulsation events: (a) equatorial projection of the satellite orbit and the local time of the low-latitude stations York and Hermanus and (b) meridional projection of the satellite orbit and the magnetic field line of the two stations. The plasmapause ($L \approx 4.9$) on this particular orbit is also shown.

event A. In the Aedey data the onset is identified from the negative excursion in the *H* component, which started at 2241 UT. In the York data the onset can be identified from the rise in the *D* component at 2241 UT. The positive *D* perturbation and the absence of a large and sudden change in *H* implies that York was located westward of the western edge of the substorm current wedge [*Clauer and McPherron*, 1974]. Event B was observed while the 2240 UT substorm was developing, according to the *H* component variation of Aedey.

Figure 2 shows the orbit of Akebono for a 30-min interval spanning the two Pi2 pulsation events. Figure 2a shows the equatorial projection of the positions of the satellite and the HER and YOR ground stations for the time interval of Figure 1. Figure 2b shows the meridional projection of the satellite orbit along with the dipole field lines indicating the *L* shells of HER and YOR. The plasmapause position on this orbit ($L \approx 4.9$) is also indicated. At the beginning of event A the satellite was at $L \approx 3.8$, $\lambda_m \approx 40°$, and at the end of event B it was at $L \approx 2.4$, $\lambda_m \approx 24°$. The satellite local time was ~2240 for both events.

The location of the plasmapause was determined by examining the plasma wave data acquired by Akebono. Figure 3 shows the electron density n_e for the orbit illustrated in Figure 2. The density was estimated from the plasma frequency f_p cutoff of the continuum radiation observed by PWS using the relation $f_p \approx 9000 n_e^{1/2}$, where the frequency is in hertz and the density is in cm^{-3}. Between 2232 and 2234 UT ($L \approx 4.9$) the density exhibited a sharp increase, from 20 to 100 cm^{-3}. This increase in density is attributed to a satellite crossing of the plasmapause.

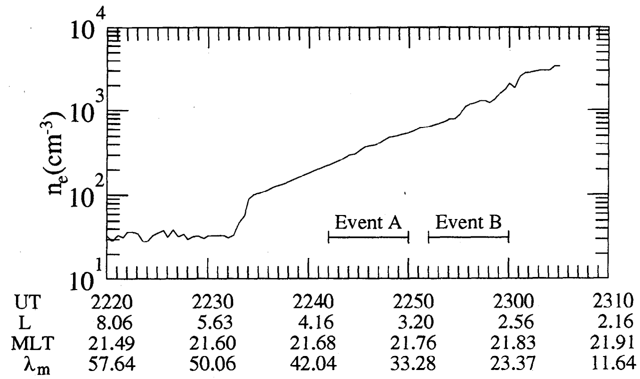


Figure 3. The electron density profile at Akebono on February 13, 1990, for the orbit illustrated in Figure 2. A sharp increase of electron density is observed between 2232 and 2234 UT. This density increase occurred at $L \approx 4.9$ and is identified as the plasmapause.

Figure 4 shows the electric and magnetic field data from the Akebono satellite for the two Pi2 events. The fields are presented using a right-handed orthogonal coordinate system: ν (radial), φ (azimuthal), and μ (field aligned). The axes for this system are defined using the International Geomagnetic Reference Field (IGRF) 1985 model magnetic field at the location of the satellite: $\mathbf{e}_\mu$ is along the model field, $\mathbf{e}_\phi$ is parallel to $\mathbf{r} \times \mathbf{e}_\mu$, where $\mathbf{r}$ is the position vector of the satellite with respect to the center of the Earth, and $\mathbf{e}_\nu = \mathbf{e}_\phi \times \mathbf{e}_\mu$ completes the triad. The angular difference between the measured and IGRF fields is less than 3° during the interval of the Pi2 activity, which assures that the coordinate system can

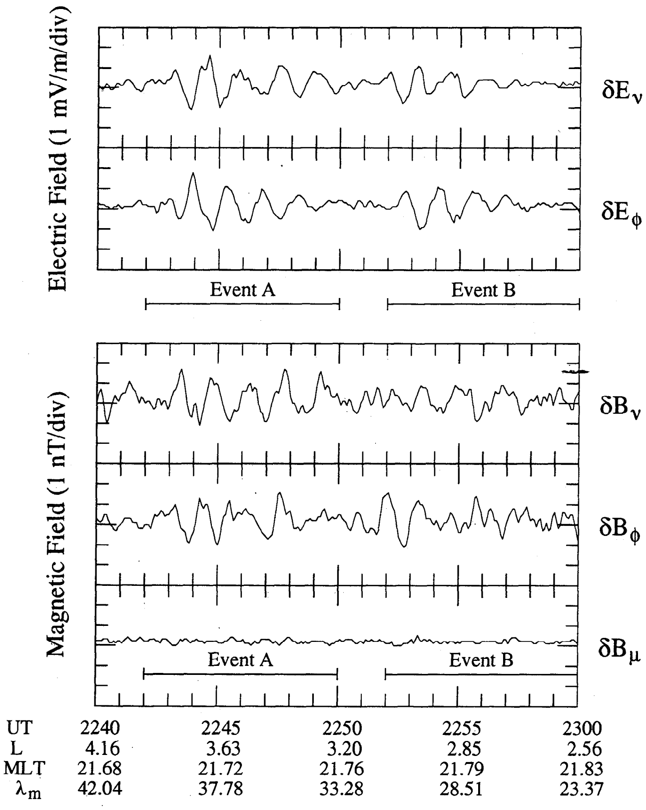


Figure 4. The electric and magnetic fields of the Pi2 pulsations at the Akebono satellite on February 13, 1990.

effectively separate perturbations transverse and parallel to the ambient magnetic field. Only the radial and azimuthal components are shown for the electric field because the parallel component is assumed to be zero in deriving the field components from the two-dimensional measurements. This assumption should be valid because the satellite was not in the auroral acceleration region where high-frequency parallel electric field fluctuations may prevail and because the pulsation under study had a spatial scale much larger than that of low-frequency waves (e.g., kinetic Alfvén waves) that have a significant parallel electric field. For both fields the trend was removed by fitting a slowly varying cubic spline to the raw data using a computer code developed by *Itonaga* [1993].

Pi2 pulsations are evident in both fields. They are recognized as two wave packets, each consisting of approximately four oscillations. As noted above, the first wave packet (event A) started at 2242 UT, at the beginning of a negative bay in the H component at Aedey. The second wave packet (event B) started ~10 min later, while the bay was still developing at a constant rate. Despite this difference in timing relative to the bay the two events exhibit essentially the same physical properties: both wave packets had an oscillation period of ~90 s; the electric field part of the pulsation had a peak-to-peak amplitude of ~3 mV/m in both the radial and azimuthal components; the magnetic field part of the pulsation was almost purely transverse ($\delta B_\nu \approx \delta B_\phi >> \delta B_\mu$), with a peak-to-peak amplitude of ~2 nT, or 0.06% of the ambient geomagnetic field; and like the electric field, the radial and azimuthal components of the magnetic field exhibited comparable amplitudes. The transverse nature of the magnetic field pulsation is in contrast to the cases observed within 16° of the magnetic equator by the CCE spacecraft [*Takahashi et al.*, 1995]. In the CCE study, the radial and compressional components were comparable to each other and larger than the azimuthal component.

Figure 5 illustrates the phase relation between observed electric $\delta\mathbf{E}$ and magnetic $\delta\mathbf{B}$ fields for event A. The orthogonal components δE_ν and δB_ϕ oscillate in phase, while δE_ϕ and δB_ν oscillate ~180° out of phase. Event B shows essentially the same feature. These phase relations are consistent with a propagating wave and are in clear contrast to transverse Pc3, Pc4, and Pc5 pulsations on the dayside as reported by *Singer and Kivelson* [1979] and *Cahill et al.* [1986]. The orthogonal components $\delta\mathbf{E}$ and $\delta\mathbf{B}$ of the dayside Pc pulsations had a 90° phase delay, indicating that they were standing Alfvén waves.

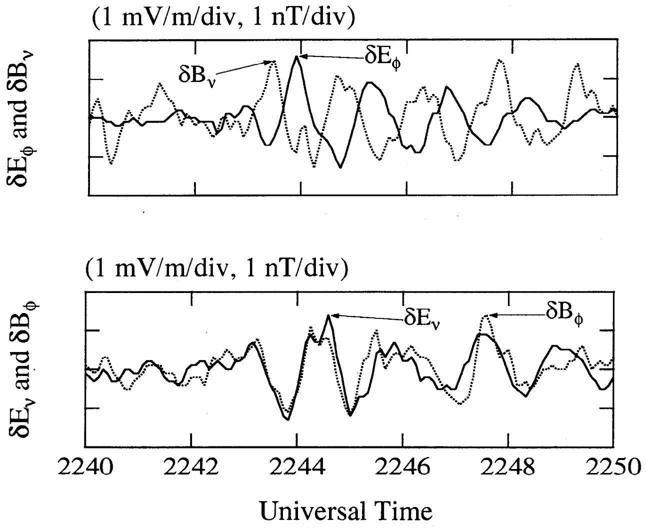


Figure 5. Comparison of the phase between the orthogonal components of the electric and magnetic fields on February 13, 1990, for event A.

Table 2. Observed Electric and Magnetic Field Perturbations and Estimated Phase Velocity

Event	δE_ϕ, mV/m	δB_ν, nT	$\delta E_\phi/\delta B_\nu$, km/s	δE_ν, mV/m	δB_ϕ, nT	$\delta E_\nu/\delta B_\phi$, km/s
A	2.8	2.7	1.0×10^3	2.7	2.2	1.2×10^3
B	2.1	1.4	1.1×10^3	1.9	2.6	7.3×10^2

The $\delta\mathbf{E}$ and $\delta\mathbf{B}$ data can be used to infer the propagation mode of the pulsations. Let us assume that the pulsations can be approximated by a plane wave with frequency ω and wave vector $\mathbf{k}$. Then $\delta\mathbf{E}$ and $\delta\mathbf{B}$ are related through Faraday's law as $\omega\delta\mathbf{B} = \mathbf{k}\times\delta\mathbf{E}$. The absence of the compressional magnetic field perturbation and the elliptical polarization suggests that we can take $\mathbf{k} \parallel \mathbf{e}_z$, which leads to

$$V_{\mathrm{ph}} \sim \frac{\omega}{k} \sim \frac{\omega}{k_z} \sim \frac{\delta E_\phi}{\delta B_\nu} \sim \frac{\delta E_\nu}{\delta B_\phi}, \qquad (1)$$

where V_{ph} is the phase velocity. From (1) the phase velocity of the pulsations can be estimated and then compared with the Alfvén velocity, given by

$$V_A = \frac{B_0}{\sqrt{\mu_0 n_e m_i}}, \qquad (2)$$

where B_0 is the strength of the ambient magnetic field, μ_0 is the magnetic permeability, n_e is the plasma number density, and m_i is the effective ion mass.

Table 2 summarizes the observed $\delta\mathbf{E}$ and $\delta\mathbf{B}$ and the phase velocity V_{ph}, estimated using (1). Table 3 summarizes the observed B_0 and n_e and the Alfvén velocity V_A, estimated using (2), assuming that the ions are all protons; that is, $m_i = m_p$, where m_p is the proton mass. For both events the Alfvén velocity is greater than $\delta E/\delta B$ by a factor of 2 or 3. On an order-of-magnitude basis, however, the observed value of $\delta E/\delta B$ (impedance) matches the Alfvén velocity, giving us assurance in treatment of the pulsation as a magnetohydrodynamic wave. The discrepancy in velocity could be reconciled if we allow for the presence of heavy ions and take the effective ion mass to be $4m_p$ (up to 20% O$^+$) or $9m_p$ (up to 50% O$^+$) instead of $1m_p$, although these values appear to be too high compared to satellite observations [*Horwitz et al.*, 1986]. Also, it is quite possible that the plane wave approximation is the source of the discrepancy.

In addition to the wave phase velocity, electromagnetic energy flux associated with the pulsations can be estimated by calculating the Poynting flux from the measured electric and magnetic fields. Figure 6 shows the three components of the Poynting flux $\mathbf{S}$ calculated using the definition

$$\mathbf{S} = \frac{\delta\mathbf{E}\times\delta\mathbf{B}}{\mu_0}. \qquad (3)$$

Table 3. Observed Magnetic Field and Plasma Density, and Estimated Alfvén Velocity

Event	B_0, nT	n_e, cm^{-3}	V_A, km/s
A	3064	226	4.4×10^3
B	3294	2082	1.6×10^3

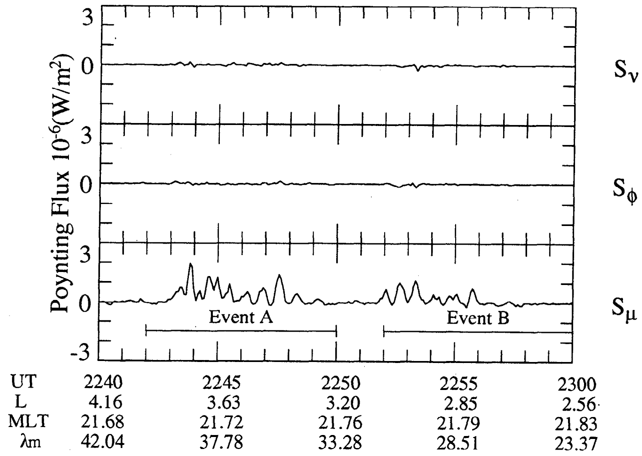


Figure 6. Poynting flux associated with the Pi2 pulsations observed at Akebono on February 13, 1990. During pulsation events A and B, only the parallel component of the Poynting flux was enhanced, and it remained positive.

The two transverse components S_v and S_ϕ are very small because of the assumption that $\delta E_\mu = 0$ and the observation that $\delta B_\mu \approx 0$.

In contrast, the parallel component S_μ (= $(\delta E_v \delta B_\phi - \delta E_\phi \delta B_v)/\mu_0$) exhibits a nonzero value during both Pi2 intervals, and the sign of S_μ is positive throughout the events. This means that the electromagnetic energy flux was directed away from the magnetic equator or toward the field line foot point closer to the satellite, if we assume that the energy flows along the ambient magnetic field. The unidirectional energy flow arises from the fact that δE_v and δB_ϕ oscillated in phase, while δE_ϕ and δB_v oscillated 180° out of phase. Our observations differ significantly from those reported by *Yeoman et al.* [1990b] for substorm-associated waves observed at geostationary orbit. For their events the field-aligned component of the Poynting flux was very small, which implies that the wave mode at geostationary orbit is different from that in the $L < 5$ region. The implication of the Poynting flux at Akebono is discussed below.

Finally, we demonstrate that the same Pi2 pulsations were observed on the ground. Figure 7 compares E_ϕ at the satellite and the H and D components at York. The York data have been detrended by using the method of *Itonaga* [1993]. If we ignore a phase delay, the perturbations in E_ϕ and D are nearly identical for both events. The strong similarity between the satellite and the ground station is unambiguous evidence that the same oscillation was observed from Akebono and on the ground. As far as the Pi2 pulsations on the ground are concerned, we find nothing unusual. Therefore we argue that the Pi2 pulsations observed by Akebono also represent Pi2 pulsations typical of that particular region in the plasmasphere.

5. Discussion

The Akebono observations presented above reveal some properties of Pi2 pulsations that have not been reported. In this section we contrast the present observations with previous CCE observations [*Takahashi et al.*, 1995] as well as with the properties of pulsations expected from the Pi2 models outlined in section 2.

5.1. Comparison of CCE and Akebono Results

In both the CCE and Akebono studies, Pi2 pulsations in the inner magnetosphere were highly coherent with Pi2 observations on the ground, suggesting that the two spacecraft observed the same physical phenomenon. CCE-ground coherence was particularly high when the satellite was at $L < 4$. This is consistent with the present Akebono events, which were observed in the plasmasphere from L = 2.4-3.8. In addition, in both studies the satellite-ground L shell separation varied considerably, up to ~3 R_E for CCE and up to ~2 R_E for Akebono. This implies that the Pi2 pulsations were not latitudinally (or radially) localized but rather were extended in the whole nightside plasmasphere. From examination of ground magnetic field data in addition to those shown in Figure 1 we have confirmed that the same Pi2 pulsations were observed from L = 1.8-6.8.

A major difference between the two studies lies in the magnetic field polarization. The Pi2 oscillations at CCE exhibited radial δB_v and compressional δB_μ components, whereas the Pi2 pulsations at Akebono were purely transverse magnetic pulsations with comparable radial δB_v and azimuthal δB_ϕ components. Could this be an indication of two physically different Pi2 oscillations? The answer is probably no. The difference likely comes from the difference in satellite latitude: the CCE observations were made at $-16° < \lambda_m < 16°$, whereas the Akebono observations were made at $24° < \lambda_m < 40°$. According to the CCE observations, δB_v is very small near the equator and increases monotonically with $|\lambda_m|$, whereas δB_μ is much larger than δB_v at the equator and varies little with $|\lambda_m|$. Because of the monotonic increase of δB_v, the $\delta B_v/\delta B_\mu$ ratio becomes greater than 1 at $\lambda_m > 10°$ in the CCE observations. This amplitude structure has been modeled by a

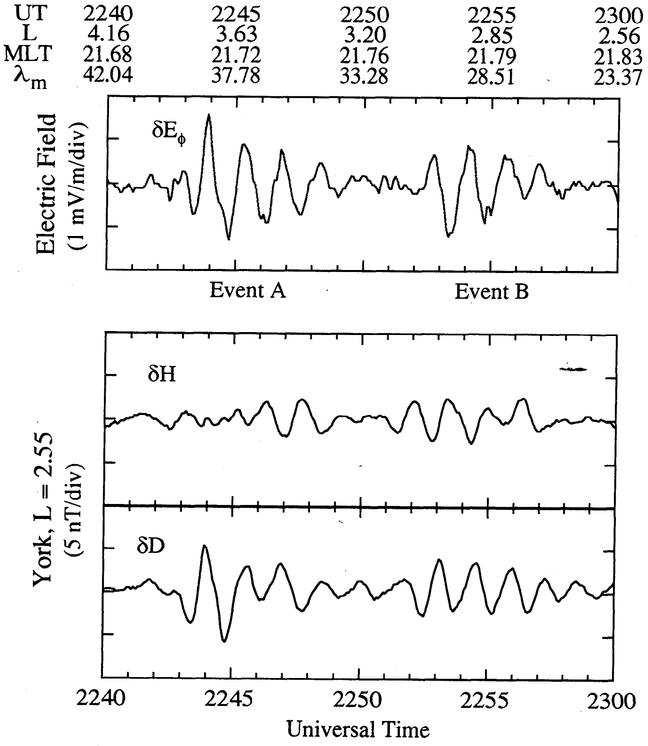


Figure 7. Comparison of Pi2 waveforms in space and on the ground observed at Akebono on February 13, 1990. The azimuthal electric field E_ϕ is used to represent the satellite Pi2.

field line displacement that is symmetric about the magnetic equator [*Takahashi et al.*, 1995]. In this model, δB_v has a node at the equator and increases with latitude, whereas δB_μ has an antinode at the equator and decreases with latitude. If the trend in $\delta B_v/\delta B_\mu$ at CCE continues to $|\lambda_m| > 16°$ as the model implies, the ratio $\delta B_v/\delta B_\mu$ will become much greater than 1 at $\lambda_m \approx 24°$ and $\lambda_m \approx 40°$, explaining the transverse Pi2 pulsation observed at Akebono. It should be noted that a symmetric pattern can be established not only by waves standing along the magnetic field line but also by waves propagating away from the equator toward north and south in a symmetric manner. We will show below by examining the relationship between the electric and magnetic fields that our Pi2 waves are consistent with the latter wave type.

In addition to the above qualitative argument based on the wave symmetry, there are quantitative studies favoring the equatorial localization of compressional waves. Using a box magnetosphere model that included the effect of an inhomogeneity parallel to the ambient magnetic field, *Southwood and Kivelson* [1986] showed that if a dense plasma is concentrated around $z = 0$ (i.e., near the magnetic equator), the amplitude of compressional magnetic perturbation is large near the magnetic equator, while the transverse components become prominent at higher latitude. A qualitatively similar result has been obtained from a numerical simulation of wave propagation in the dipole magnetosphere [*Lee*, 1996]. These results are consistent with the compressional Pi2 pulsations observed by CCE at low λ_m and transverse Pi2 pulsations observed by Akebono at high λ_m.

5.2. Comparison of the Akebono Observations With Pi2 Models

This section assesses various Pi2 models in light of the Akebono observations.

5.2.1. Plasmapause surface wave. By definition, the amplitude of a surface wave decreases with distance from the surface on which the wave is excited. For a simple planar geometry the amplitude A as a function of position x can be given in the form

$$A(x) = A_s \exp[-2\pi |x - x_s| / \lambda], \tag{4}$$

where A_s is the amplitude at the surface, x_s is the position of the surface, and λ is the wavelength along the surface [*Lanzerotti et al.*, 1981]. For a rough estimate of the amplitude variation of plasmapause surface waves we adopt a box magnetosphere model in which x corresponds to geocentric distance and $x = x_s$ represents the plasmapause. We assume two representative wavelengths $\lambda = 2\pi x_s$ and πx_s, corresponding to angular azimuthal wavenumbers m of 1 and 2, respectively. These m values are within the range reported from multipoint ground observations [*Yumoto*, 1986]. We set the location of the plasmapause at $x_s = 4.9\ R_E$ to be consistent with our Akebono observation. Figure 8a shows the model amplitude. Figure 8b shows the Pi2 amplitude at Akebono, $(\delta B_v^2 + \delta B_\phi^2)^{1/2}$, normalized by the ground amplitude at Hermanus, $(\delta H^2 + \delta D^2)^{1/2}$. It is evident that the observed amplitude was larger when the satellite was closer to the Earth, which is opposite to the property of a surface wave. From this comparison we conclude that the observed Pi2 pulsations cannot be explained by a surface wave on the plasmapause.

5.2.2. Shear Alfvén mode resonances. Shear Alfvén resonances or standing Alfvén waves can be excluded for the observed Pi2 pulsations for several reasons. First, the wave period did not change with the satellite's radial distance, and second, the phase delay between the magnetic and electric perturbations indicated a propagating wave rather than a standing wave. A quantitative discussion of these issues is presented below.

Ionospheric reflection is an essential ingredient for the excitation of standing Alfvén waves. We examined whether the nightside ionospheric condition is appropriate for standing Alfvén waves by solving the Alfvén wave equation with realistic ionospheric boundary conditions. We used the numerical method described by *Newton et al.* [1978] for the axisymmetric toroidal mode [*Cummings et al.*, 1969; *Orr and Matthew*, 1971] to obtain the ionospheric damping rate and the associated parameters. This technique is the same as that used by *Takahashi et al.* [1996] in an analysis of nightside transient toroidal waves. Although our Pi2 events were not pure toroidal modes, use of the toroidal equation should give a reasonable estimate of the general damping rate of Alfvén waves with different polarizations, as Newton et al. suggested by comparing poloidal and toroidal calculations. In the Newton et al. formulation the ionospheric boundary condition is given by

$$\delta E_v = \pm \frac{1}{\mu_0 \Sigma_p} \delta B_\phi, \tag{5}$$

where Σ_p is the height-integrated Pedersen conductivity [*Hughes*, 1974; *Hughes and Southwood*, 1976]. For Σ_p we adopted an empirical ionospheric conductivity model given by *Wallis and Budzinski* [1981], which covers a latitude Φ range

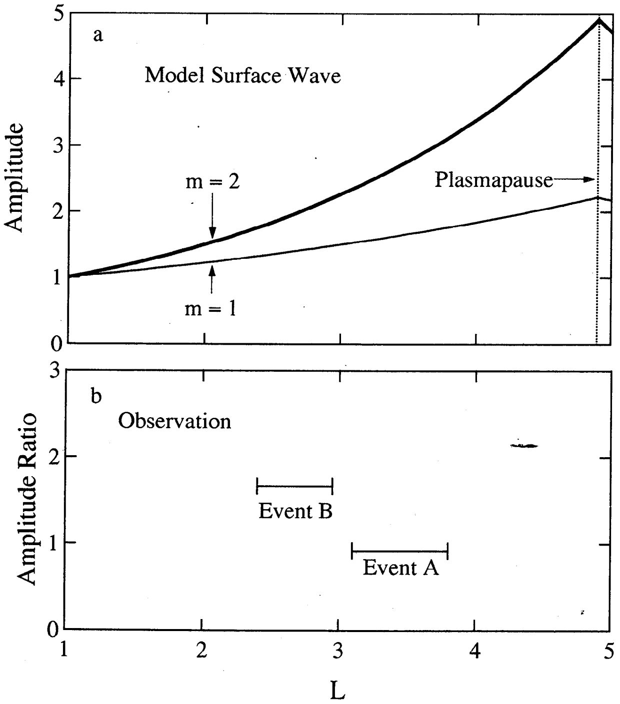


Figure 8. (a) Amplitude profile of a plasmapause surface wave for two values of the wavelength parallel to the surface. The amplitude is normalized by the value at $x = 1$, corresponding to the ground. (b) Amplitude of observed magnetic field perturbation at Akebono, $(\delta B_v^2+\delta B_\phi^2)^{1/2}$, normalized by Hermanus magnetic field perturbation $(\delta H^2+\delta D^2)^{1/2}$ for the two Pi2 events.

of 60°-84°. For $\Phi \leq 60°$ we used a constant value Σ_p ($\Phi = 60°$). The Alfvén velocity, which also needs to be specified, was modeled by assuming an $n = n_{eq}(r_{eq}/r)^3$ density variation along the dipole field line and using the observed electron density to specify n_{eq} for each value of L. Two effective ion mass values were assumed: $m_i = m_p$ (all protons) and $m_i = 2.35m_p$, the latter value taken from *Moore et al.* [1987] and *Horwitz et al.* [1986]. We assumed that there was no temporal variation in the model parameters during the two Pi2 events.

Figure 9 shows the model and calculated parameters as a function of L. Figures 9a-9d are the equatorial electron density, the equatorial Alfvén velocity, the real part f_r of the eigenfrequency of the fundamental toroidal mode standing Alfvén wave, and the normalized damping rate f_i/f_r, where f_i is the imaginary part of the eigenfrequency, respectively. In Figure 9c a solid curve is used for the $m_i = m_p$ case, a dotted curve is used for the $m_i = 2.35m_p$ case, and a dotted line is used for the observed Pi2 frequency. The L ranges of the observed Pi2 pulsations are indicated by the two horizontal bars in the density plot (Figure 9a).

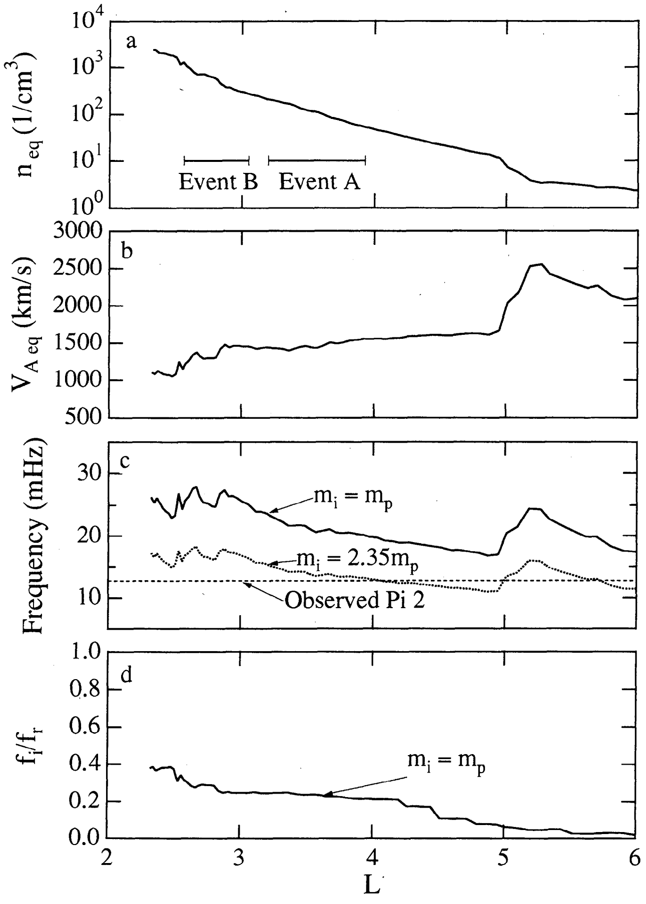


Figure 9. (a) L dependence of the estimated equatorial electron density on February 13, 1990. The density is estimated from the observation presented in Figure 3, assuming that the magnetic field is a dipole field and the electron density varies along the field line as $n = n_{eq}(r_{eq}/r)^3$. (b) The Alfvén velocity V_A (km/s) at the equator is calculated using the equatorial plasma density shown in Figure 9a and assuming an all-proton ($m_i = m_p$) plasma. (c) The fundamental toroidal mode frequency for the above plasmasphere model. The dotted curve is the frequency for $m_i = 2.35m_p$. The horizontal dashed line at 13 mHz indicates the observed Pi2 frequency. (d) Calculated damping rate. This rate is estimated on the basis of an empirical ionospheric conductivity model given by *Wallis and Budzinski* [1981].

Figure 9 shows two important results. First, the real part of the frequency varies with L and thus does not match the observed Pi2 frequency. For the $m_i = m_p$ case the calculated toroidal frequency decreases from 26 mHz at $L = 3$ to 17 mHz at $L = 4.9$. The frequency is consistently higher than the observed Pi2 frequency of ~13 mHz. For the $m_i = 2.35m_p$ case the model frequency is 17-11 mHz for $L = 3$-4.9, which is closer to the observed Pi2 frequency. However, the model frequency still strongly depends on L, which is inconsistent with the observations. Unless we assume a highly artificial variation in ion mass with L, we cannot match the model and observed frequencies. We conclude that the Pi2 frequency is not determined by the local toroidal mode frequency in the plasmasphere. This conclusion is consistent with the common frequency observed on the ground from L = 1-5 for individual Pi2 events [e.g., *Bjornsson et al.*, 1971; *Yeoman and Orr*, 1989; *Yumoto et al.*, 1994].

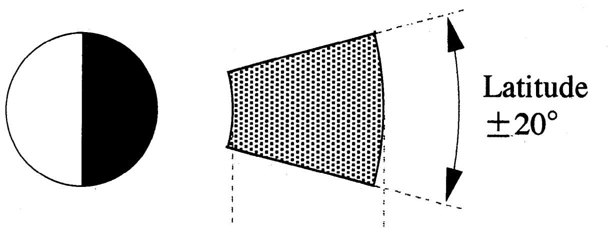
Second, it is evident that the ionosphere heavily damps standing Alfvén waves, so that observable Alfvénic resonances in the inner magnetosphere are unlikely on the nightside. The damping rate is nearly constant for $2.5 < L < 4.2$; it decreases with L for $L > 4.2$ because of the increase of the ionospheric Pedersen conductivity toward the subauroral region. In Figures 9c and 9d we find a frequency of ~20 mHz (period ~50 s) and a damping rate of ~0.2 to be typical for the toroidal oscillation in the region $2.5 < L < 4.2$. Using these values, we estimate the typical duration of toroidal oscillation to be ~30 s, which means that a standing Alfvén wave is damped before completing one oscillation unless energy is continuously supplied. Because the observed Pi2 pulsation lasted for ~4 cycles or ~400 s, this model result means that the observed Pi2 pulsations are not impulsively excited standing Alfvén waves. To maintain the Pi2 at the Akebono satellite, energy must have been continuously fed from an external oscillating source or a driver wave.

5.2.3. Cavity mode resonance. The model results just given imply that treating the ionosphere as a perfectly reflecting boundary for confining cavity mode oscillations [*Kivelson and Southwood*, 1986; *Southwood and Kivelson*, 1986; *Zhu and Kivelson*, 1989; *Allan et al.*, 1986a, 1986b; *Lin et al.*, 1991; *Lee*, 1996] is inappropriate when considering Pi2 pulsations. Cavity models for nightside events definitely need to incorporate loss through the ionosphere as well as loss from the radial boundaries [*Fujita and Glassmeier*, 1995].

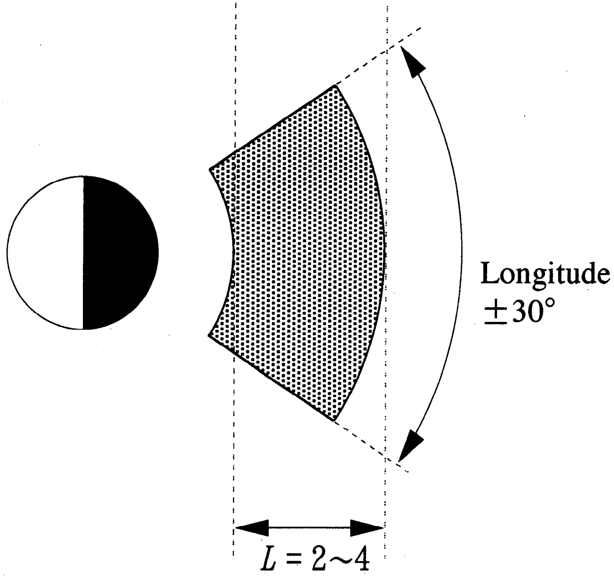
One could still argue that a cavity mode is responsible for the Pi2 pulsations observed by Akebono by referring to the equatorial localization of compressional energy described above [*Southwood and Kivelson*, 1986; *Lee*, 1996]. Whether the compressional waves drive the transverse Pi2 pulsations can be tested by the following simple calculation. The concept of the calculation is illustrated in Figure 10. We assume that near the magnetic equator Pi2 pulsations have the properties of a plasmaspheric cavity oscillation. The total energy stored in the cavity in the form of compressional magnetic field oscillation is given by [e.g., *Crowley et al.*, 1989]

$$\varepsilon = V \frac{\delta B_\mu^2}{\mu_0}, \qquad (6)$$

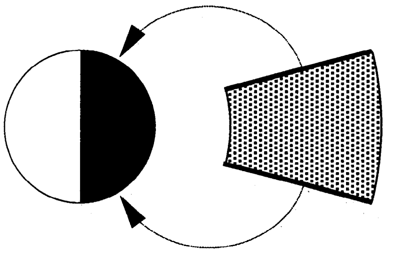
where V is the effective volume of the cavity and δB_μ is the



(a) Meridional Projection



(b) Equatorial Projection



(c) Escaping Poynting Flux

Figure 10. A plasmaspheric cavity mode model used for discussing the energy budget of Pi2 pulsations. (a) The meridional projection of the cavity. The plasmaspheric cavity oscillation is assumed to be confined within $L = 2\text{-}4$, and $-20° \leq \lambda_m \leq 20°$. (b) The equatorial projection of the model. The longitudinal extent of the plasmaspheric cavity oscillation is assumed to be ±30°. (c) Poynting flux escaping from the northern and southern boundaries of the plasmaspheric cavity mode. The flux is absorbed completely at the ionosphere.

amplitude of the compressional component. For a rough estimate we assume that the cavity has a volume given by $L = [2, 4]$, $\lambda_m = [-20°, 20°]$, and $\phi = [-30°, 30°]$, which gives $V = \iiint dr\, r d\theta\, r \sin\theta\, d\phi \approx 4.26\pi R_E^3$. The total compressional mode energy ε can be estimated as follows. From *Takahashi et al.* [1995] we find that the average satellite-to-ground amplitude ratio $\delta B_\mu / \delta H$ is ~0.3, where δH is the Pi2 amplitude in the H component at low latitude ($L < 2$). For the Akebono events the amplitude in the H component at Hermanus was ~3 nT, so we estimate the corresponding δB_μ in the equatorial magnetosphere to be ~1 nT. By substituting this value in (6) we get $\varepsilon \approx 1.4 \times 10^9$ J.

Next, we assume that the stored compressional energy escapes from the northern and southern boundaries of volume V. If we consider only the electromagnetic energy, the total escaping energy flux is given by the Poynting flux S_μ, times the total area of the northern and southern boundaries. The total area is $\sim 3.8\pi R_E^2$ (see Figure 10c), and the measured Poynting flux is $\sim 3.4 \times 10^{-7}$ W/m^2 for event A and $\sim 1.5 \times 10^{-7}$ W/m^2 for event B. Therefore the total energy flux integrated over the northern and the southern boundaries is 1.7×10^8 W for event A and 7.3×10^7 W for event B. Dividing the cavity mode energy ε by the magnitude of the escaping flux, we find that the energy of the equatorial cavity oscillation can maintain the escaping Poynting flux for only ~10-20 s. This result means that the equatorial compressional oscillation will be damped in the same timescale unless it is externally driven. We conclude that an equatorially confined cavity mode oscillation is also an unlikely source for the Pi2 pulsations observed at Akebono.

5.2.4. External driver. The energy budget consideration suggests that we look for an oscillation source, or a driver wave, external to the plasmasphere. A driver wave was considered as an alternative to the cavity mode by *Takahashi et al.* [1992]. With the Akebono observations indicating some difficulty with a simple cavity mode, we need to give serious consideration to the external driver model. *Takahashi et al.* [1992] suggested auroral zone transient Alfvén waves (oscillating current wedge) and compressional oscillations associated with near-Earth current sheet disruption as possible drivers. However, spectral analysis of CCE magnetometer data taken at $L \approx 7$ did not confirm such sources [*Takahashi et al.*, 1995].

Recently, near-Earth compressional disturbances have received new attention in relation to Pi2 pulsations. *Kepko and Kivelson* [1996] reported that a Pi2 oscillation started immediately following a bursty bulk flow (BBF) event. They suggested that the BBF compressed the flux tubes in the inner magnetosphere and that the compressional disturbance converted into a shear Alfvén wave which propagated down to the ionosphere as a Pi2 pulsation. In a related theoretical study, *Itonaga et al.* [1997] showed that the relative phase between the compressional components at CCE and the H components at Kakioka reported by *Takahashi et al.* [1992, 1995] cannot be explained by a simple cavity mode oscillation. Itonaga et al. argued that Pi2 pulsations in the magnetosphere are forced oscillations driven by a damped wave incident on the outer boundary. BBFs might play the role of the external damped wave. We note, however, that this scenario requires BBFs to turn on and off with a Pi2 period. It is not known whether BBFs have such an inherent periodicity.

6. Conclusions

We have studied two Pi2 pulsations observed from the Akebono satellite on a single pass through the plasmasphere. Data from Akebono included measurements of the magnetic field, electric field, and plasma density. The following observations were made of the Pi2 events: (1) At Akebono, located at $L = 2.5\text{-}3.8$ and $\lambda_m = 24°\text{-}40°$, the magnetic perturbations of the Pi2 pulsations were strongly transverse, and the Poynting flux of the pulsations was directed from the equator to the ionosphere. (2) The same Pi2 pulsations were observed at ground stations located at $L = 1.8$ and $L = 6.8$ and at local times close to that of Akebono. We compared these observations with previous CCE observations made in a similar L range and proposed that in the magnetosphere, Pi2 pulsations within $\lambda_m \approx \pm 20°$ are in a compressional mode, whereas outside this region they are in a transverse mode.

In an attempt to understand the origin of the Pi2 pulsations observed at Akebono, we compared the characteristics of the observed Pi2 pulsations with those of standing Alfvén waves modeled using the observed plasmaspheric electron density data. The estimated Alfvén resonance frequency varied with L, unlike the frequency of the observed Pi2. Moreover, the estimated damping rate of the Alfvén resonance was so large that the Pi2 pulsation could not be described by a standing Alfvén wave. Although the strong damping was consistent with the Poynting flux directed to the ionosphere, we faced a difficulty in explaining the long duration of the Pi2 pulsations. That is, an energy source other than standing Alfvén waves was required for the Pi2 pulsations.

Taking a plasmaspheric cavity mode as a possible source for the Akebono Pi2 pulsations, we evaluated the duration of the transverse magnetic pulsations. It was found that the cavity mode energy can maintain the transverse oscillation for only ~10-20 s, which implies that the compressional Pi2 pulsations found at the equator in previous CCE studies also may be driven by a source external to the plasmasphere. What constitutes the external source remains to be identified.

It must be cautioned that the present study is based on only two events observed on a single Akebono pass. Obviously, we cannot generalize the semiquantitative arguments presented above. However, we do emphasize the need to observe Pi2 events in the plasmasphere at various latitudes in both magnetic and electric fields. The importance of using both magnetic and electric fields has been clearly demonstrated.

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References

Allan, W., E. M. Poulter, and S. P. White, Hydromagnetic wave coupling in the magnetosphere-Plasmapause effects on impulse-excited resonances, *Planet. Space Sci.*, *34*, 1189-1200, 1986a.

Allan, W., S. P. White, and E. M. Poulter, Impulse-excited hydromagnetic cavity and field-line resonances in the magnetosphere, *Planet. Space Sci.*, *34*, 371-385, 1986b.

Bjornsson, A., O. Hillebrand, and H. Voelker, First observational results of geomagnetic Pi2 and Pc5 pulsations on a north-south profile through Europe, *Z. Geophys.*, *37*, 1031-1042, 1971.

Cahill, L. J., N. G. Lin, M. J. Engebretson, D. R. Weimer, and M. Sugiura, Electric and magnetic observations of the structure of standing waves in the magnetosphere, *J. Geophys. Res.*, *91*, 8895-8907, 1986.

Chen, L., and A. Hasegawa, A theory of long-period magnetic pulsations, 1, Steady state excitation of field line resonance, *J. Geophys. Res.*, *79*, 1024-1032, 1974a.

Chen, L., and A. Hasegawa, A theory of long-period magnetic pulsations, 2, Impulse excitation of surface eigenmode, *J. Geophys. Res.*, *79*, 1033-1037, 1974b.

Clauer, C. R., and R. L. McPherron, Mapping the local time-universal time development of magnetospheric substorms using mid-latitude magnetic observations, *J. Geophys. Res.*, *79*, 2811-2820, 1974.

Crowley, G., W. J. Hughes, and T. B. Jones, Observational evidence of cavity modes in the Earth's magnetosphere, *J. Geophys. Res.*, *92*, 12,233-12,240, 1987. (Correction, *J. Geophys. Res.*, *94*, 1555-1555, 1989.)

Cummings, W. D., R. J. O'Sullivan, and P. J. Coleman, Jr., Standing Alfvén waves in the magnetosphere, *J. Geophys. Res.*, *74*, 778-793, 1969.

Fujita, S., and K.-H. Glassmeier, Magnetospheric cavity resonance oscillations with energy flow across the magnetopause, *J. Geomagn. Geoelectr.*, *47*, 1277-1292, 1995.

Fukunishi, H., Polarization changes of geomagnetic Pi2 pulsations associated with the plasmapause, *J. Geophys. Res.*, *80*, 98-110, 1975.

Fukunishi, H., et al., Magnetic field observations on the Akebono (EXOS-D) satellite, *J. Geomagn. Geoelectr.*, *42*, 385-409, 1990.

Hayakawa, H., et al., Electric field measurement on the Akebono (EXOS-D) satellite, *J. Geomagn. Geoelectr.*, *42*, 371-384, 1990.

Horwitz, J. L., R. H. Comfort, and C. R. Chappell, Plasmasphere and plasmapause characteristics measured by DE-1, *Adv. Space Res.*, *6*(3), 21, 1986.

Hughes, W. J., The effect of the atmosphere and ionosphere on long period magnetospheric micropulsations, *Planet. Space Sci.*, *22*, 1157-1172, 1974.

Hughes, W. J., and D. J. Southwood, An illustration of modification of geomagnetic pulsation structure by the ionosphere, *J. Geophys. Res.*, *81*, 3241-3246, 1976.

Itonaga, M., Data smoothing using a piecewise cubic polynomial (in Japanese), *Nippon Ouyou Suuri Gakkai Ronbunshi*, *3*, 59-71, 1993.

Itonaga, M., A. Yoshikawa, and K. Yumoto, One-dimensional transient response of the inner magnetosphere at the magnetic equator, 2, Analysis of waveforms, *J. Geomagn. Geoelectr.*, *49*, 49-68, 1997.

Kepko, L., and M. Kivelson, Simultaneous observations of Pi2 oscillations and earthward hurtling bursty bulk flows (abstract), *Eos Trans. AGU*, *77*(46), Fall Meet. Suppl., F611, 1996.

Kivelson, M. G., and D. J. Southwood, Coupling of global magnetospheric MHD eigenmodes to field line resonances, *J. Geophys. Res.*, *91*, 4345-4351, 1986.

Lanzerotti, L. J., C. G. Maclennan, and T. Hasegawa, Polarization characteristics of hydromagnetic waves at low geomagnetic latitudes, *J. Geophys. Res.*, *86*, 5500-5506, 1981.

Lee, D.-H., Dynamics of MHD wave propagation in the low-latitude magnetosphere, *J. Geophys. Res.*, *101*, 15,371-15,386, 1996.

Lester, M., and D. Orr, Correlations between ground observations of Pi2 geomagnetic pulsations and satellite plasma density observations, *Planet. Space Sci.*, *31*, 143-160, 1983.

Lester, M., W. J. Hughes, and H. J. Singer, Polarization patterns of Pi2 magnetic pulsations and the substorm current wedge, *J. Geophys. Res.*, *88*, 7958-7966, 1983.

Lester, M., W. J. Hughes, and H. J. Singer, Longitudinal structure in Pi2 pulsations and the substorm current wedge, *J. Geophys. Res.*, *89*, 5489-5494, 1984.

Lester, M., H. J. Singer, D. P. Smits, and W. J. Hughes, Pi2 pulsations and the substorm current wedge: Low-latitude polarization, *J. Geophys. Res.*, *94*, 17,133-17,141, 1989.

Lin, C. A., L. C. Lee, and Y. J. Sun, Observations of Pi2 pulsations at a very low latitude (L = 1.06) station and magnetospheric cavity resonances, *J. Geophys. Res.*, *96*, 21,105-21,113, 1991.

Moore, T. E., D. L. Gallagher, J. L. Horwitz, and R. H. Comfort, MHD wave breaking in the outer plasmasphere, *Geophys. Res. Lett.*, *14*, 1007-1010, 1987.

Newton, R. S., D. J. Southwood, and W. J. Hughes, Damping of geomagnetic pulsations by the ionosphere, *Planet. Space Sci.*, *26*, 201-209, 1978.

Orr, D., and J. A. D. Matthew, The variation of geomagnetic micropulsation periods with latitude and the plasmapause, *Planet. Space Sci.*, *19*, 897-905, 1971.

Oya, H., and K. Tsuruda, Introduction to the Akebono (EXOS-D) satellite observations, *J. Geomagn. Geoelectr.*, *42*, 367-370, 1990.

Oya, H., A. Morioka, K. Kobayashi, M. Iizima, T. Ono, H. Miyaoka, T. Okada, and T. Obara, Plasma wave observation and sounder experiments (PWS) using the Akebono (EXOS-D) satelliteinstrumentation and initial results including discovery of the high altitude equatorial plasma turbulence, *J. Geomagn. Geoelectr., 42,* 411-442, 1990.

Saito, T., Geomagnetic pulsations, *Space Sci. Rev., 10,* 319-412, 1969.

Saito, T., and S. Matsushita, Solar cycle effects on geomagnetic Pi2 pulsations, *J. Geophys. Res., 73*, 267-286, 1968.

Saito, T., T. Sakurai, and Y. Koyama, Mechanism of association between Pi2 pulsation and magnetospheric substorm, *J. Atmos. Terr. Phys., 38,* 1265-1277, 1976.

Sakurai, T., and R. L. McPherron, Satellite observations of Pi2 activity at synchronous orbit, *J. Geophys. Res., 88*, 7015-7027, 1983.

Singer, H. J., and M. G. Kivelson, The latitudinal structure of Pc 5 waves in space: Magnetic and electric field observations, *J. Geophys. Res., 84*, 7213-7222, 1979.

Southwood, D. J., Some features of field line resonances in the magnetosphere, *Planet. Space Sci., 22,* 483-491, 1974.

Southwood, D. J., and M. G. Kivelson, The effect of parallel inhomogeneity on magnetospheric hydromagnetic wave coupling, *J. Geophys. Res., 91*, 6871-6876, 1986.

Southwood, D. J., and W. F. Stuart, Pulsations at the substorm onset, in *Dynamics of the Magnetosphere*, edited by S.-I. Akasofu, pp. 341-355, D. Reidel, Norwell, Mass., 1980.

Stuart, W. F., A mechanism of selective enhancement of Pi2's by the plasmapause, *J. Atmos. Terr. Phys., 36,* 851-859, 1974.

Stuart, W. F., Arrays of magnetometers operated in N. W. Europe, in *The IMS Source Book: Guide to the International Magnetosphere Study Data Analysis,* edited by C. T. Russell and D. J. Southwood, pp. 141-152, AGU, Washington, D. C., 1982.

Stuart, W. F., P. M. Brett, and T. J. Harris, Mid-latitude secondary resonance in Pi2's, *J. Atmos. Terr. Phys., 41*, 65-75, 1979.

Sutcliffe, P. R., The association of harmonics in Pi2 power spectra with the plasmapause, *Planet. Space Sci., 23*, 1581-1587, 1975.

Sutcliffe, P. R., and K. Yumoto, Dayside Pi2 pulsations at low latitudes, *Geophys. Res. Lett., 16*, 887-890, 1989.

Sutcliffe, P. R., and K. Yumoto, On the cavity mode nature of low-latitude Pi2 pulsations, *J. Geophys. Res., 96,* 1543-1551, 1991.

Takahashi, K., S. Ohtani, and K. Yumoto, AMPTE CCE observations of Pi2 pulsations in the inner magnetosphere, *Geophys. Res. Lett., 19,* 1447-1450, 1992.

Takahashi, K., S. Ohtani, and B. J. Anderson, Statistical analysis of Pi2 pulsations observed by the AMPTE CCE spacecraft in the inner magnetosphere, *J. Geophys. Res., 100*, 21,929-21,941, 1995.

Takahashi, K., B. J. Anderson, and S. Ohtani, Multisatellite study of nightside transient toroidal waves, *J. Geophys. Res., 101,* 24,815-24,825, 1996.

Wallis, D. D., and E. E. Budzinski, Empirical models of height integrated conductivities, *J. Geophys. Res., 86,* 125-137, 1981.

Yeoman, T. K., and D. Orr, Phase and spectral power of mid-latitude Pi2 pulsations: Evidence for a plasmaspheric cavity resonance, *Planet. Space Sci., 37*, 1367-1383, 1989.

Yeoman, T. K., D. K. Milling, and D. Orr, Pi2 pulsation polarization patterns on the U. K. sub-auroral magnetometer network (SAMNET), *Planet. Space Sci., 38*, 589-602, 1990a.

Yeoman, T. K., D. Orr, and A. Pedersen, Ground-satellite correlations and geostationary orbit energy flow at substorm onset, *Planet. Space Sci., 38*, 241-253, 1990b.

Yeoman, T. K., M. Lester, D. K. Milling, and D. Orr, Polarization, propagation and MHD wave modes of Pi2 pulsations: SABRE/SAMNET results, *Planet. Space Sci., 39*, 983-998, 1991.

Yeoman, T. K., M. P. Freeman, G. D. Reeves, M. Lester, and D. Orr, A comparison of midlatitude Pi2 pulsations and geostationary orbit particle injections as substorm indicators, *J. Geophys. Res., 99*, 4085-4093, 1994.

Yumoto, K., Generation and propagation mechanisms of low-latitude magnetic pulsations - A review, *J. Geophys., 60*, 79-105, 1986.

Yumoto, K., H. Osaki, K. Fukao, K. Shiokawa, Y. Tanaka, S. I. Solovyev, G. Krymskij, E. F. Vershinin, V. F. Osinin, and 210° MM Magnetic Observation Group, Correlation of high- and low-latitude Pi2 magnetic pulsations observed at 210° magnetic meridian chain stations, *J. Geomagn. Geoelectr., 46*, 925-935, 1994.

Zhu, X., and M. G. Kivelson, Global mode ULF pulsations in a magnetosphere with a nonmonotonic Alfvén velocity profile, *J. Geophys. Res., 94*, 1479-1485, 1989.

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