Pi2 pulsations observed with the Polar satellite and ground stations: Coupling of trapped and propagating fast mode waves to a midlatitude field line resonance

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Abstract. Simultaneous measurements from the Polar satellite and several ground stations of two substorm-related Pi2 pulsation events (separated by $\sim$6 min) provide evidence for radially trapped and propagating fast mode waves and a coupled field line resonance (FLR). The Pi2 pulsations were observed at five ground stations located between 2130 and 2330 magnetic local time (MLT) ranging from L=1.83 to 3.75, which showed nearly identical waveforms in the H component with a frequency of $\sim$20 mHz. Five additional ground stations located between L=4.48 and $\sim$15 (on similar meridians) recorded weaker less-correlated signals. The pulsations were also detected both simultaneously and with a time delay of $\sim$38 s at two low-latitude stations (L=1.17 and 1.23) on the dayside at $\sim$1030 and $\sim$0612 MLT, respectively, indicating the global extend of the pulsations. The nightside ground data showed an amplitude maximum and a phase reversal in the H component between L=3.4 and 3.75. During the oscillations the Polar satellite moved (on the same meridian as the ground stations in the nightside) from 14° to 10° magnetic latitude and from L=4.1 to 3.7. Electric and magnetic field measurements also showed two Pi2 pulsation events ($\sim$20 mHz) in both the compressional (B_z and E_y) and transverse (B_y and E_x) mode components with waveforms almost identical to the ground signals. Whereas the first Pi2 had a standing wave structure in the compressional mode, the second Pi2 was a propagating wave. Both Pi2s had standing wave signatures in the transverse mode. The amplitude of the compressional magnetic field component (B_z) was $\sim$40% of that of the azimuthal component (B_y). Although the two Pi2 events showed equal amplitudes in the H component of ground data, Polar recorded much larger oscillations in the azimuthal magnetic field component (B_y) of the first Pi2 event; the fast mode amplitude (B_z) was nearly unchanged for both Pi2s. This suggests that Polar was at or near a localized FLR excited by the oscillations of the fast mode waves. During the in situ FLR observation, Polar's footpoint was closest to the ground stations which recorded the amplitude maximum and the phase reversal in the H component.

1. Introduction

Ultralow frequency (ULF) waves are a common occurrence in the magnetosphere. Ground- and satellite-based studies have greatly improved our understanding of these

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waves. Cavity mode models have been considered as a generation mechanism for a number of ULF waves such as Pc3-5 and Pi2 (see references below). A geomagnetic cavity mode is a resonance of large regions in the magnetosphere. The resonance is formed by compressional waves confined between reflecting boundaries, allowing discrete resonances to form within the cavity. In recent years the cavity mode has been extended to include variations in the boundary conditions, which lead to models such as global cavity mode, plasmaspheric cavity mode, waveguide mode, virtual trapped resonance, and virtual scattering resonance. We refer the reader to the works of *Lee and Kim* [1999], *Fujita et al.* [2000], and *Samson et al.* [1992a] for descriptions of these variations. In the work presented herein we will use the terms cavity-type mode and trapped fast mode interchangeably, both of which are defined as standing compressional waves in the radial direction.

The least understood ULF waves are Pi2 pulsations, which are waves in the period range from 40 to 150 s. Theoretical

and numerical work supporting a Pi2 generation mechanism based on a cavity-type mode has been presented by a number of authors [e.g., *Allan et al.*, 1996; *Lee and Lysak*, 1999]. Observational studies in space [*Takahashi et al.*, 1995], but mostly from the ground [e.g., *Sutcliffe and Yumoto*, 1989; *Yeoman and Orr*, 1989; *Lin et al.*, 1991], show evidence for a cavity-type-mode induced Pi2. In this paper we present ground and space observations of two successive Pi2 pulsation events ($\sim$20 mHz). The first event was consistent with a cavity-type mode. The interpretation of the second event is less clear, because of differences in the space signature compared to the first event. The Pi2 pulsations were associated with a substorm and thus fall into the class of Pi2s that receives the most attention and which has long been used as a substorm indicator [*Saito*, 1969]. Recent studies also show evidence for quiet time Pi2 pulsations [*Sutcliffe*, 1998].

We briefly describe the main properties of the cavity-type mode as derived from theoretical models and as partially observed in experimental studies before we present our observations in the next section. Firstly, because the cavity-type mode is a global resonance, the spatial extend is very large. It is not well established which parts of the magnetosphere can sustain cavity-mode oscillations. Evidence for cavity-type modes in the dayside portion of the magnetosphere [e.g., *Kivelson et al.*, 1984; *Kim et al.*, 1998] and the plasmasphere [e.g., *Sutcliffe and Yumoto*, 1991; *Kim and Takahashi*, 1999] has been presented. Simultaneous observations of Pi2 pulsations in the dayside and nightside demonstrate their global extent [*Sutcliffe and Yumoto*, 1991; *Shinohara et al.*, 1997]. The nightside region of the outer magnetosphere (beyond the plasmapause) has also been considered, but observational evidence does not yet exist. In the case of the plasmaspheric cavity mode the ionosphere acts as the inner boundary, and the plasmapause acts as the outer one. If the plasmapause is a reasonably good but imperfect reflector, then fast mode waves being launched in the outer magnetosphere during times of substorms can penetrate the plasmapause potential barrier and subsequently be partially trapped in the plasmasphere [e.g., *Lee*, 1996; *Lee and Kim*, 1999]. In this case, space observations should either not detect oscillation outside the plasmasphere or, more likely, detect only smaller oscillation owing to wave energy escaping through the plasmapause.

Secondly, cavity oscillations have the same frequency throughout the cavity, and the frequencies are discrete. An exact calculation of the eigenfrequencies is impossible because it would require knowing the entire state of the cavity. Numerical calculations for a specific model suggest that the eigenfrequencies of the fundamental and second plasmaspheric cavity mode lie in the range from 10 to 15 mHz and from 26 to 28 mHz, respectively [*Lee*, 1998]. These estimates depend among other physical quantities on the cavity size. During periods of larger geomagnetic activity, the plasmasphere is reduced in size [*Chappell*, 1972], and hence higher resonance frequencies are expected for larger Kp values, which is confirmed by observational studies [*Hamilton*, 1982]. Ground-based observations at low latitudes and mid-latitudes have shown Pi2 pulsations of $\sim$10-30 mHz [e.g.,

Sutcliffe and Yumoto, 1991; *Yeoman and Orr*, 1989; *Lin et al.*, 1991].

Thirdly, the oscillations of a cavity-type mode are essentially in the poloidal (radial and compressional) components. In the statistical study of Pi2 pulsations ($L \leq 5$) by *Takahashi et al.* [1995], using data from the Active Magnetospheric Particle Tracer Explorers (AMPTE)/CCE, it was found that the poloidal magnetic field components dominate. In addition, the amplitude and phase variations were also consistent with a cavity-type mode. A purely poloidal oscillation of field lines, however, is an idealized case, requiring that the azimuthal wave number m is zero. For any other m the poloidal mode couples to the toroidal (or shear Alfvén) mode [*Chen and Hasegawa*, 1974; *Southwood*, 1974; *Kivelson and Southwood*, 1986]. The coupling is most efficient when the cavity eigenfrequency matches the field line eigenfrequency, leading to another resonance, the field line resonance (FLR). The FLR is confined to a smaller region of L shells, because for L shells farther away from the FLR the resonance condition is not met. There are a number of studies that have reported FLR on the dayside [e.g., *Fukunishi and Lanzerotti*, 1974; *Singer et al.*, 1982; *Takahashi and McPherron*, 1982; *Cahill et al.*, 1986] and nightside [*Hughes and Grard*, 1984]. However, these studies investigated Pc pulsations. A study by *Takahashi et al.* [1996] reported nightside FLR (called transient toroidal waves by the authors) in the Pi2 frequency range and in association with substorm onset. However, the authors concluded that it is not likely that these cases of FLR were directly related to mid-latitude to low-latitude Pi2s observed on the ground, mostly because the frequency varied with L value in contrast to ground Pi2s. Hence there have so far been no observations in space of FLR that are directly related to substorm-associated Pi2 pulsations.

Fourthly, although the frequency of compressional magnetic field oscillations is the same everywhere in the cavity, this is not so for the phase. Even for the fundamental eigenmode, different regions oscillate out of phase [e.g., *Allan et al.*, 1986]. The amplitude and phase characteristic for a pure fundamental mode, assuming there is no coupling to FLR, is such that the field line displacement amplitude has an antinode between the inner and outer boundaries, and a phase shift of $180°$ at the location of the antinode. This displacement antinode is manifested as a node in the compressional component in space and the H component on the ground. The extensive satellite-based study by *Takahashi et al.* [1995] on Pi2 pulsations showed that there is a $180°$ phase reversal in the compressional component around $L=4$. The authors concluded that their observations were consistent with a cavity-type mode. Numerous ground-based observations have also shown a $\sim$$180°$ phase reversal in the H component between $L$$\sim$3 to 4 [e.g., *Lester and Orr*, 1989; *Yeoman and Orr*, 1989]. For example, *Yeoman and Orr* [1989] concluded that their ground Pi2 observations were consistent with a cavity-type mode interpretation because of the $180°$ phase reversal and a lack of a coincident amplitude maximum in H as described above. An alternative interpretation for a $180°$ phase reversal is based on the FLR model. FLR also produces a $180°$ phase shift [*Southwood*, 1974].

However, an important difference is that this phase reversal coincides with an amplitude maximum in H. *Bjornsson et al.* [1971] and *Fukunishi* [1975] have observed these signatures and concluded the existence of FLR at $L \sim 4$.

Fifthly, the compressional magnetic field oscillations are standing waves in the radial direction. Ground observations alone are not sufficient to determine this property. The study by *Kim et al.* [1998] showed, on the basis of cross-phase analysis between the H component of one low-latitude ground station and the compressional component measured by the AMPTE/CCE satellite, that the dayside Pc3 pulsations under investigation were consistent with a radially standing compressional wave. Similar results were reported by *Takahashi et al.* [1995], who investigated the phase and amplitude variations for Pi2s observed by AMPTE/CCE and one low-latitude ground station. Although these two studies show indirect evidence for standing compressional waves, there has so far been no direct evidence based on the phase relationship between in situ electric and magnetic field measurements associated with fast mode waves. Just as in the case of FLR, the corresponding compressional field perturbations (E_y and B_z) should be phase-shifted by 90° in the case of a standing compressional wave.

Although there is observational support for the cavity-type mode in space and on ground in association with Pi2 pulsations, all of the properties mentioned above have not been observed together for one event. One of the two substorm-related Pi2 events presented here shows all of these properties. Data come from the Polar satellite and several ground stations located in the nightside and dayside during the Pi2 pulsations. To our knowledge, this is the most complete description of a single Pi2 event. In particular, there exists only limited information in the literature on the electrodynamics (i.e., both electric and magnetic field signature) of Pi2s in space. In situ measurements presented herein show for the first time the simultaneous presence of both fast mode waves (standing and propagating) and standing shear Alfvén waves at the same location associated with substorm-related Pi2s. This suggests that Polar was at or near a localized FLR excited by the oscillations of the fast mode waves. During the in situ FLR observation, Polar's footpoint was closest to the ground stations which recorded an amplitude maximum and a 180° phase reversal in the H component.

2. Instrumentation

The observations presented here are from the Polar satellite and several ground stations. The Polar satellite is placed in an $\sim$18-hour polar orbit (80° inclination), with perigee and apogee of 2.2 and 9 R_E (geocentric distance), respectively. Hence Polar's orbit is very suitable for a study of different magnetospheric regions. Polar measures the full three-dimensional vector of both the electric and magnetic fields, which allows a better characterization of Pi2 pulsations than only the magnetic field as mostly done by previous studies. For this study we incorporated data from the University of California (UC) Berkeley Electric Field Instrument [*Harvey et al.*, 1995], the University of Californaia at Los Angeles (UCLA) Fluxgate Magnetometer [*Russell et al.*, 1995], and the University of Iowa Hydra Plasma Instrument [*Scudder et al.*, 1995]. The electric field is determined from a measurement of the electric potential difference between pairs of current-biased spherical sensors. These sensors are deployed at the ends of three orthogonal pairs of booms with tip-to-tip separations of 100 and 130 m (in the spin plane) and 13.8 m (along the spin axis). The three-axis electric field vector is sampled at 20 samples s^{-1}. The magnetic field vector is sampled at 8.3 samples s^{-1} by the three-dimensional fluxgate magnetometer. The particle detector provides measurements of electron energy flux at 1.2- and 13.8-s time resolutions, the latter of which is used in this study, in the energy range from 12 eV to 18 keV. Ground data come from the Sub-Auroral Magnetometer Network (SAMNET), the International Monitor for Auroral Geomagnetic Effects (IMAGE), the Hermanus ground station in South Africa, the Kakioka ground station in Japan, and the Makaha ground station in Hawaii. The locations of the stations used in this study are shown in Table 1. SAMNET and IMAGE stations and Hermanus lie within 2 hours of local time. Kakioka and Makaha are $\sim$9 and 13 hours to the east of SAMNET, respectively. SAMNET, Hermanus, Kakioka, and Makaha data are shown at time resolutions of 5, 1, 1,

Table 1. Ground Magnetometer Stations

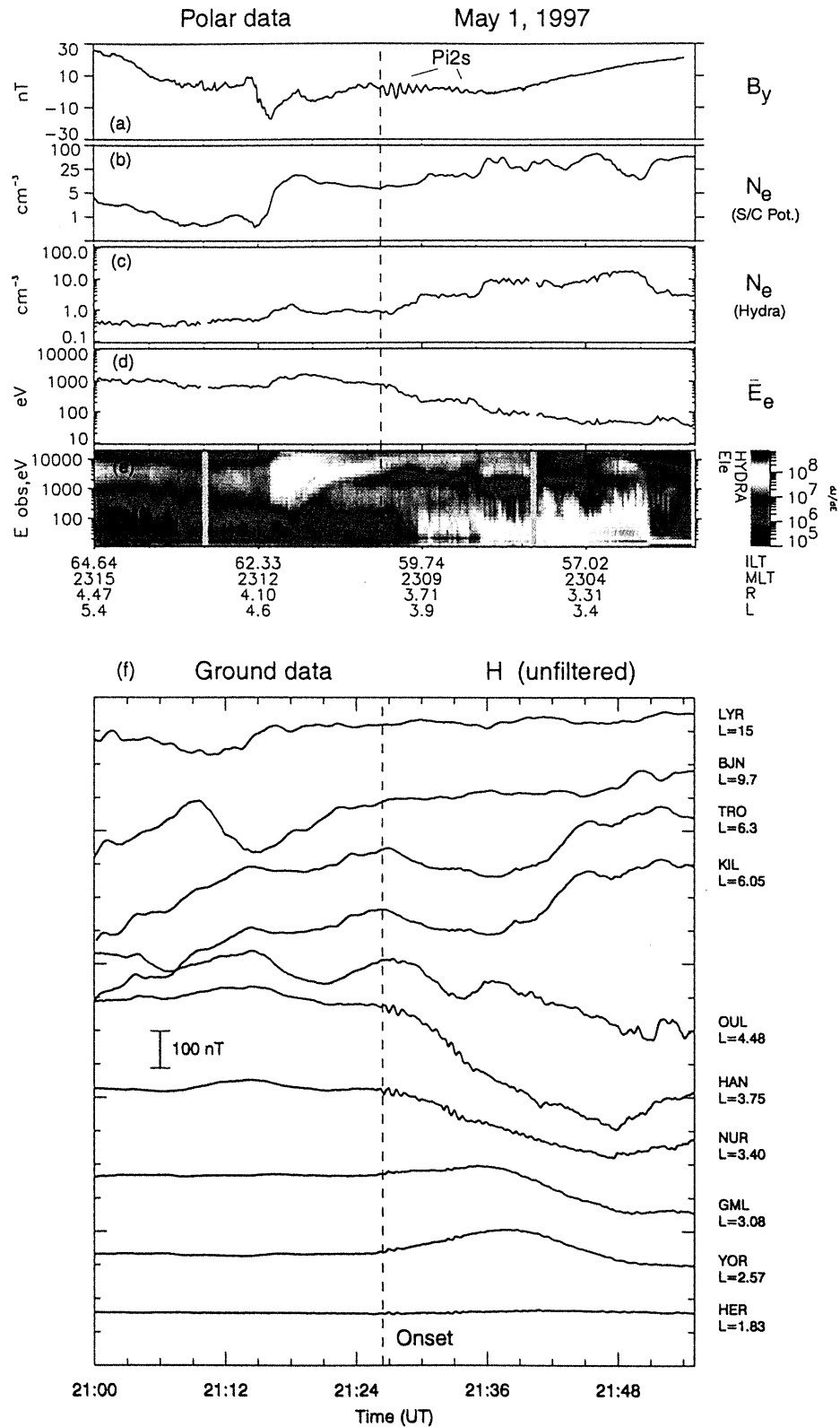| Station Name	Code	GLAT, deg	GLON, deg	L
Longyearbyen	LYR	75.12	113.00	$\sim$15
Bear Island	BJN	71.33	108.73	9.7
Tromso	TRO	66.54	103.44	6.3
Kilpisjarvi	KIL	65.78	104.31	6.05
Oulu	OUL	61.52	105.94	4.48
Hankasalmi	HAN	58.60	105.18	3.75
Nurmijarvi	NUR	56.80	102.74	3.40
Glenmore	GML	54.91	78.22	3.08
York	YOR	50.93	79.00	2.57
Hermanus	HER	-42.42	81.93	1.83
Kakioka	KAK	27.2	208.5	1.23
Makaha	MAK	22.7	269.4	1.17

Plate 1. Satellite- and ground-based observations of the Pi2s on May 1, 1997. (a) East-west perturbation of the magnetic field, (b) electron density determined from the spacecraft potential, (c) electron density determined from Hydra, (d) mean energy of electrons, (e) electron energy spectrum, and (f) ground magnetic field records of the H component (unfiltered) of high- to low-latitude stations on the nightside within 2 hours of local time of Polar's orbit. The onset time of the substorm occurred at $\sim$2126 UT indicated by the vertical dashed line. Pulsations were present until $\sim$2200 UT.

Meridional Projection
(0600-1200 MLT dayside; 2100-2400 MLT nightside)

Equatorial Projection
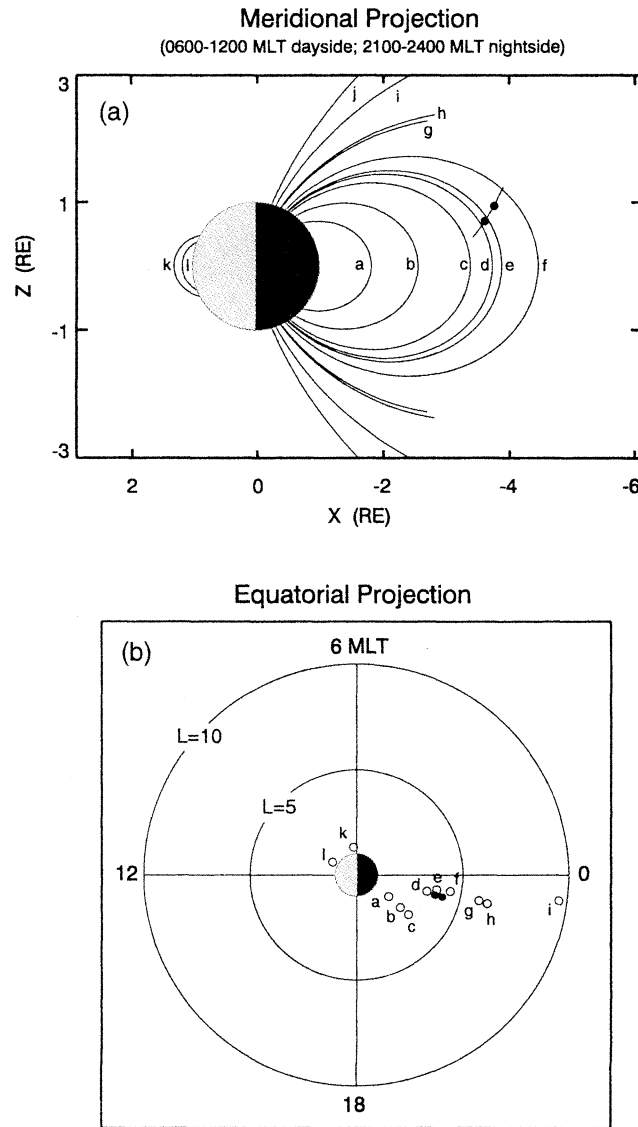
Figure 1. (a) Meridional projection of dipole field lines that are conjugate to ground stations used in this study and a partial Polar orbit on May 1, 1997, indicating the locations of two Pi2 pulsation events. The letters stand for the following: a,HER; b,YOR; c,GML; d,NUR; e,HAN; f,OUL; g,KIL; h,TRO; i,BJN; j,LYR; k,KAK; l,MAK. Please see Table 1 for station abbreviations. (b) Equatorial projection. The circles show the interceptions with the equatorial plane of those field lines that are connected to the ground stations. LYR ($L \sim 15$) is not shown.

and 2 s, respectively. IMAGE data are shown at 1- and 10-s time resolutions.

3. Overview

On May 1, 1997, two successive Pi2 pulsation events were recorded by the Polar satellite and by several ground magnetometers. Figure 1a shows schematically the dipole field lines that are connected to the ground stations used in this study and a partial Polar orbit indicating the times of the two Pi2 events. The magnetic local time (MLT) for all nightside ground stations and Polar ranged between 2130 and 2330 MLT (Figure 1b). The stations on the dayside, Kakioka (KAK) and Makaha (MAK), were located at 0612 and 1030 MLT, respectively.

During the Pi2 pulsations, Polar was on an inbound orbit moving from $L=4.1$ (14° magnetic latitude (MLAT)) to $L=3.7$ (10° MLAT). Plate 1a shows the Pi2s as recorded in the azimuthal component (B_y) of the magnetic field. Plate 1b shows the plasma density inferred from the spacecraft potential. Plates 1c-1e show the density, mean energy, and energy spectrum of electrons determined from the Hydra particle detector. Plate 1f shows the H component of ground magnetometer data from several ground stations located in the nightside during the Pi2 events.

In order to exclude certain Pi2 models, it is important to identify the plasma regime in which the satellite is located during the pulsations. From the Hydra data (Plates 1d-1e) it can be seen that the Pi2s occurred in the plasma sheet.

The electron mean energy was between 200 and 600 eV, which are typical values for the plasma sheet. Furthermore, Plate 1e shows a very structured electron spectrum, owing to the fact that this time period occurred during large geomagnetic activity with $Kp \geq 5$. Because the lower energy cutoff of Hydra is 12 eV, it cannot record plasmaspheric plasma with energies of ~ 1 eV. Hence, on the basis of Hydra data, it cannot be ruled out that the plasmasphere extended into the plasma sheet, making Polar occupy both regions simultaneously. Spacecraft potential measurements converted into density estimates [*Pedersen*, 1995] have successfully been used by other studies to identify plasmapause crossings (H. Laakso et al., Polar observations of electron density distribution in the Earth's magnetosphere, submitted to *Journal of Geophysical Research*, 2000). Six minutes before Polar recorded the first Pi2 event, Polar encountered an increase in the density from 1 to 20 particles cm^{-3} determined from the spacecraft potential (Plate 1b). The density calculation is accurate to within a factor of 2-3. The plasmapause, however, is associated with density increases of up to 100 particles cm^{-3} and more. The increase at ~ 2115 UT coincides with an increase in particle energy flux (Plate 1e) determined from Hydra. This suggests that the density increase in Plate 1b is caused by the energetic particles, because the spacecraft potential is also affected by particle flux in the plasma sheet. Additional density increases can be seen in both Plate 1b and 1c (different magnitudes), tracking each other fairly consistently, indicating that the spacecraft potential measurements responded to the flux of the energetic particles (≥ 12 eV). The two density measurements deviate mostly after ~ 2150 UT. The density increase shown in Plate 1b is thus most likely due to particles below the energy cutoff of Hydra, i.e., plasmaspheric particles. Because spacecraft potential data are not available after 2155 UT, it is not clear whether this increase is the plasmapause or a detached plasma region. Alternatively, we attempted to determine the plasmapause location from plasma wave data. Generally, upon crossing the magnetic equator, Polar observes electron cyclotron harmonic emission. This is not the case on this orbit. It is also typical to observe a rather rapid density gradient as determined from narrowband upper hybrid emission, as the satellite enters or exits the plasmasphere. There is some indication of such emission (f=80 kHz) beginning perhaps at ~ 2143:30 UT (D. Menietti, personal communication, 2000).

Because of the difficulties in identifying the plasmapause, we also considered the statistical location of the plasmapause. An empirical relationship between Kp and the plasmapause location [*Chappell*, 1972] places the plasmapause at $L \leq 4$ for $Kp \geq 5$, which were values prior to and during the Pi2 pulsations. Motion of the plasmapause during very dynamic conditions and detached plasma regions from the main plasmasphere can make an identification of the plasmapause more complicated in some cases [*Chappell*, 1974; *Takahashi et al.*, 1999]. We conclude that it was not possible to locate the plasmapause, although there is some indication on the basis of density measurements, upper hybrid emission, and the empirical relationship that the Pi2 pulsations occurred outside the plasmasphere.

During the time of the Pi2 pulsations, Polar's magnetic footpoint traversed the SAMNET and IMAGE magnetometer chains. The SAMNET and IMAGE stations used in this study cover an L range from 2.57 to ~ 15. Together with the Hermanus station (L=1.83) the latitudinal extent of the Pi2 pulsations on the ground can be determined. Plate 1f shows unfiltered ground magnetograms of the H component from 10 stations. The start of the Pi2 pulsations at 2126 UT can most clearly be seen at stations with $L \leq 4$. However, a careful inspection (see section 5) also reveals oscillations at higher-latitude stations with the same frequency but smaller amplitude; that is, the Pi2 pulsations were also recorded in the auroral zone. The onset time of the first Pi2 coincided with the negative turning of the H component at Hankasalmi (HAN) and Nurmijarvi (NUR), indicating that these Pi2s are substorm-related. The onset time also coincided with the onset of the Pi2s observed at Polar's location (Plate 1a).

4. Satellite Data

We now present additional satellite data for the Pi2 pulsations on May 1, 1997. Figure 2 displays the perturbations of the three-dimensional electric and magnetic field vectors for the two Pi2 pulsations. The perturbation fields were calculated by calculating 10-s averages and detrending each com-
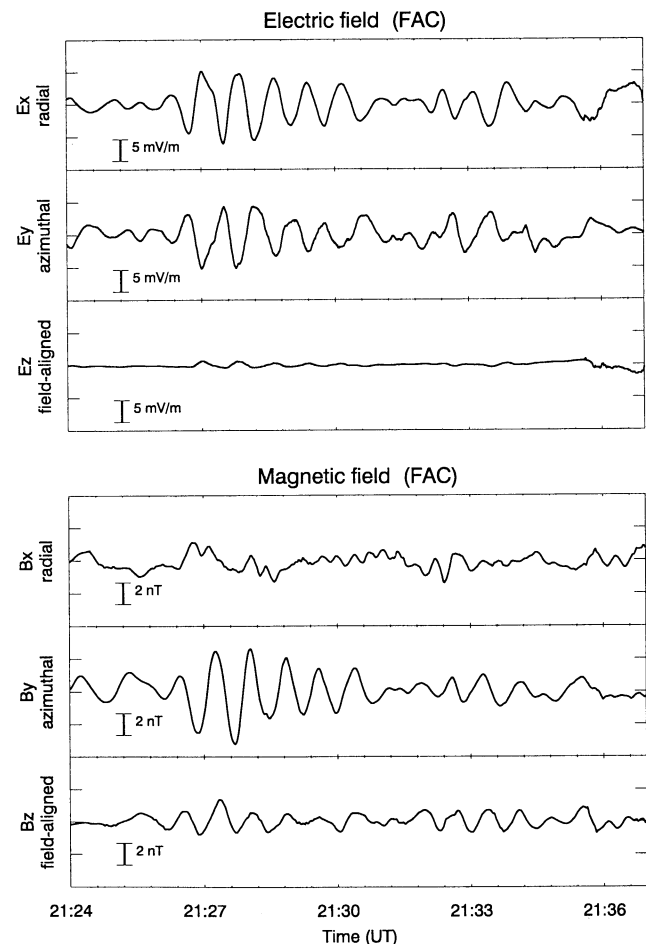

Figure 2. Electric and magnetic fields in a field-aligned coordinate system of the Pi2 events observed by Polar on May 1, 1997. Data were averaged (10 s) and detrended (150 s).
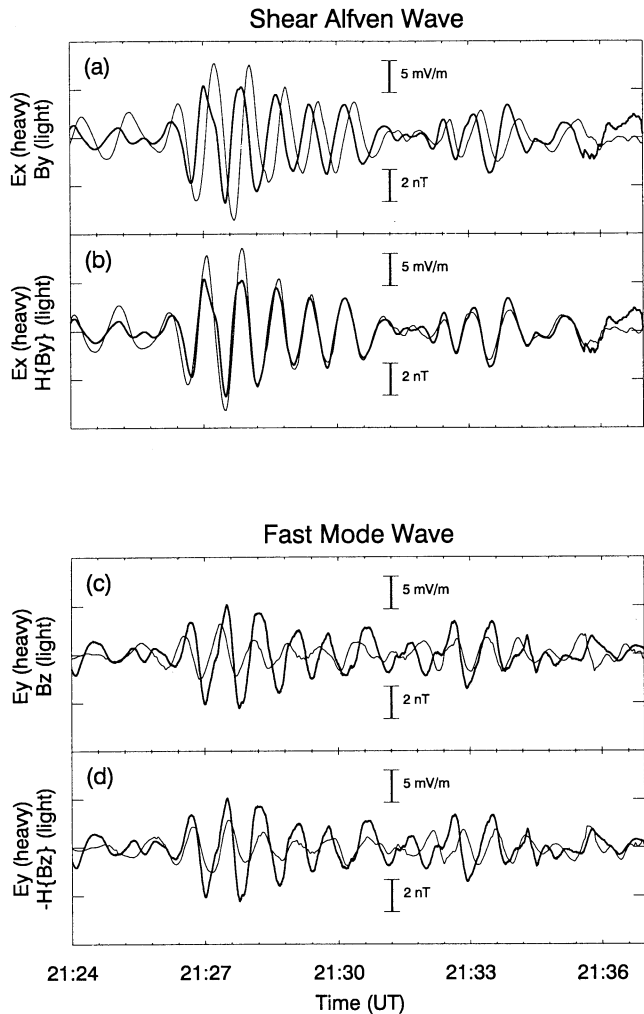
Shear Alfven Wave

Fast Mode Wave

Figure 3. Comparison of the waveforms of the electric and magnetic components on May 1, 1997, that are associated with (a) shear Alfvén waves and (c) fast mode waves. A phase shift of 90° indicates a standing wave structure. (b,d) The electric field plotted with the Hilbert-transformed magnetic field (see text for further description). These data suggest a trapped fast mode wave (first Pi2 at ~2127 UT) and a propagating fast mode wave (second Pi2 at ~2133 UT) which are both coupled to field line resonance (FLR). Data were averaged (10 s) and detrended (80 s).

ponent of the fields by subtracting a 150-s running average from the original data. The data are presented in a field-aligned coordinate system, in which the z axis is parallel to the local magnetic field **B**, the x axis is perpendicular to **B** and points away from the Earth in the meridional plane, and the y axis is perpendicular to **B** and points in an easterly direction. Both the electric and magnetic fields show oscillations with a period of ~50 s (20 mHz). Two Pi2 pulsation events can be discerned, starting at ~2126 and ~2132 UT. The oscillations in the electric field were largest and of approximately equal amplitude in the E_x (radial) and E_y (azimuthal) components. The field-aligned component E_z was much smaller as expected. In contrast, the magnetic field shows clear oscillations with the same frequency in B_y and B_z but no 50-s oscillations in B_x. With respect to the magnetic field, two observations need to be emphasized. Firstly,

for the first Pi2 event, Polar recorded a much stronger azimuthal component compared to the compressional component. The compressional component was ~40% in magnitude compared to the azimuthal component. Secondly, while the amplitude of the compressional component was similar for both Pi2 events, the amplitude of the azimuthal component for the first Pi2 was more than twice as large as that of the second Pi2. In comparison, the two Pi2 events showed equal amplitudes in the ground data as will be shown in section 5. These are properties of localized FLR coupled to a compressional mode which will be further supported below.

To facilitate further interpretation of the electric and magnetic field observations, Figure 3 shows the corresponding perpendicular electric and magnetic field components overlaid for the two MHD wave modes. Figures 3a and 3b show the shear Alfvén wave components (transverse mode), and Figures 3c and 3d show the components associated with the fast mode wave (compressional mode). Pi2 pulsations were present in both modes. Phase shifts of 90° between the electric and magnetic field components (Figures 3a and 3c) indicate standing wave structures. The Hilbert transform ($HT\{\}$) of the magnetic field is overlaid on the electric field in Figures 3b and 3d to allow more precision about phase shifts. A Hilbert transform of a signal shifts all Fourier components of the signal by 90°. For a purely standing wave the fields would appear in phase. This is indeed the case to a high degree for most parts of the shear Alfvén wave associated with the two Pi2 pulsations investigated here (Figure 3b). However, a close inspection shows that at the beginning of the first Pi2 (~2126:30 UT) the corresponding peaks of E_x and $HT\{B_y\}$ do not exactly coincide. This seems to indicate the transition toward a standing wave.

The fast mode wave shows signatures of both traveling and propagating waves. The electric field and Hilbert-transformed magnetic field (Figure 3d) of the first Pi2 (from 2126 to 2130 UT) are almost in phase, indicating a standing wave, in addition to a small traveling component. The second Pi2, on the other hand, shows that the electric and magnetic signals are in phase (Figure 3c), or equivalently, the electric and Hilbert-transformed magnetic fields are out of phase by ~90° (Figure 3d), which is indicative of a traveling wave. We thus conclude that at Polar's location a radially trapped fast mode (first Pi2) and a propagating fast mode (second Pi2) were present.

The presence of both modes at the same location, having the same frequency and having the amplitude variations as described above in conjunction with Figure 2, suggests field line resonance, confined to a finite L range, which is coupled to a fast mode wave in a way that was theoretically shown by *Kivelson and Southwood* [1986]. The authors used a box model of a nonuniform plasma and showed that a large-scale compressional mode can transfer energy to localized FLR where the frequency of the compressional mode matches the resonant frequency of the local field line. This condition yields a singular point in the governing differential equation. The FLR can thus reach larger amplitudes than the compressional mode. Additional effects such as dissipation or dispersion eventually limit the growth of the resonance as pointed out by the authors.
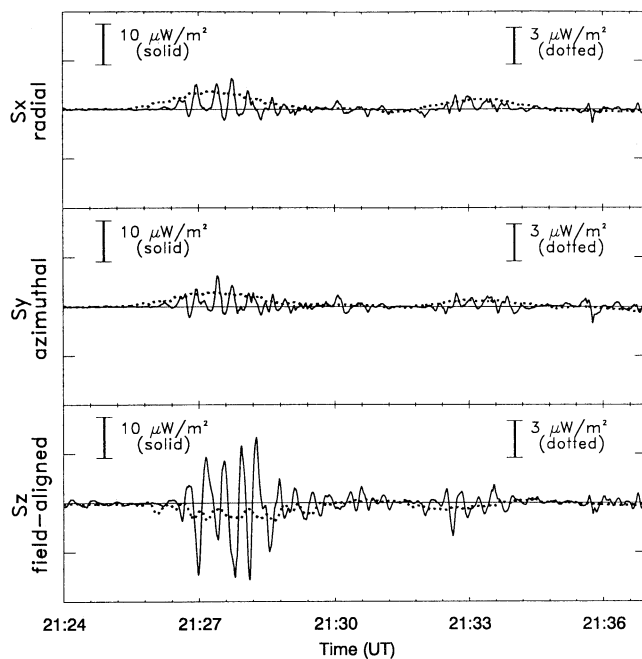
Figure 4. Poynting flux, presented in a field-aligned coordinate system, associated with the Pi2 pulsations on May 1, 1997. The dotted line shows the Poynting vector after low-pass filtering (120 s) the instantaneous vector components (solid line).

The effect of the various phase shifts can best be seen in the Poynting vector, which is shown in Figure 4. The same field-aligned coordinate system is used as before. The three panels show the band-pass-filtered (10 and 80 s) vector components, computed from the full three-dimensional electric and magnetic field vector. The dotted line shows the Poynting vector after low-pass filtering (120 s) the three vector components, which has the effect of integrating the Poynting vector over several wave periods [*Hughes and Grard*, 1984]. We emphasize that Poynting flux calculations are strongly dependent on the model subtraction and on the period range chosen for filtering. The field-aligned component (S_z) of the Poynting vector, which is associated with the FLR, oscillates with a peak amplitude of ~20 and ~8 μW m^{-2} for the first and second Pi2, respectively. The dotted line indicates a small net energy flow away from the ionosphere. The perpendicular components $(S_x$ and $S_y)$ show the oscillations of the fast mode, having a net energy flow in an antisunward and easterly direction. The energy transfer between the fast mode and the coupled FLR has been theoretically investigated by *Kivelson and Southwood* [1986]. Bearing in mind the limitations of the simple model used, the authors concluded that the fast mode should be accompanied by a net perpendicular inward Poynting flux toward the resonant L shell. However, the Pi2s on May 1, 1997, show a net Poynting flux perpendicular to the ambient magnetic field that propagated away from the Earth and in an easterly direction. The outward propagation can be explained by allowing for a more efficient inner boundary (e.g., the ionosphere) for the reflection of compressional waves than a possible outer reflector, which is a reasonable assumption.

The electrodynamic properties of the Pi2s on May 1, 1997, differ from those reported by *Osaki et al.* [1998] using the Akebono satellite. The authors characterized electric and magnetic fields of two successive Pi2 pulsation events within the plasmasphere ($L = 2.4 - 3.8$, MLAT=24-40°, and ~2240 MLT). No compressional component in **B** was detected, but instead clear oscillations in the radial and azimuthal components with comparable amplitudes were recorded. This resulted in a Poynting flux parallel to the ambient magnetic field and directed toward the near ionosphere, with little indication of ionospheric reflection [*Osaki et al.*, 1998]. In the study by *Takahashi et al.* [1996], calculating damping rates for nightside transient toroidal waves, it was argued that toroidal oscillations are highly damped for $L \le 4$. This led to the conclusion that standing Alfvén waves could not sustain more than one oscillation without a continuous driver. Assuming that the model calculation by *Takahashi et al.* [1996] has accurate estimates of ionospheric damping, there is still no inconsistency with the Pi2s on May 1, 1997, and their observations. The presence of the large-scale compressional mode associated with the Pi2 can provide the necessary energy source for the localized FLR.

5. Ground Data

We have so far presented satellite observations which show evidence of a radially trapped fast mode and a propagating fast mode in the nightside and FLR excited by the fast mode. To investigate how the space Pi2 observations relate to ground Pi2 observations, we now present further ground magnetometer data.

The band-pass-filtered H component ground data are shown in Figure 5 together with Polar's field-aligned (compressional) perturbation magnetic field for comparison. Note that the scales and time resolutions are different for different panels. Two Pi2 pulsations with a frequency of ~20 mHz can be seen separated by ~6 min in the ground data. The oscillations are strongest and most coherent for stations at $L \le 4$. However, oscillations at Longyearbyen (LYR) are similar enough to York (YOR), for example, to conclude that the two signals are from the same source. Similarly, for the second Pi2 event the signals at Tromso (TRO) and Kilpisjarvi (KIL) are similar in frequency (not in amplitude) to that at HAN. The amplitudes and durations of the first and the second Pi2 event are very similar for stations at L≤4. The amplitudes are largest at HAN and NUR. These observations show that most of the oscillation power is found at $L \le 5$. Combined with the satellite observations of a trapped fast mode wave for the first Pi2, a cavity-type mode is a possible generation mechanism, with the ionosphere as the inner boundary and the outer boundary located between L=3.75 and 5. As shown in section 3, it was not conclusive based on satellite data at what L value the plasmapause was located during the Pi2 pulsations. A numerical simulation of MHD waves in the nightside magnetosphere by *Lee and Lysak* [1999], who included an imperfect plasmapause boundary, showed that power at discrete frequencies was found inside as well as outside the plasmasphere up to large L values
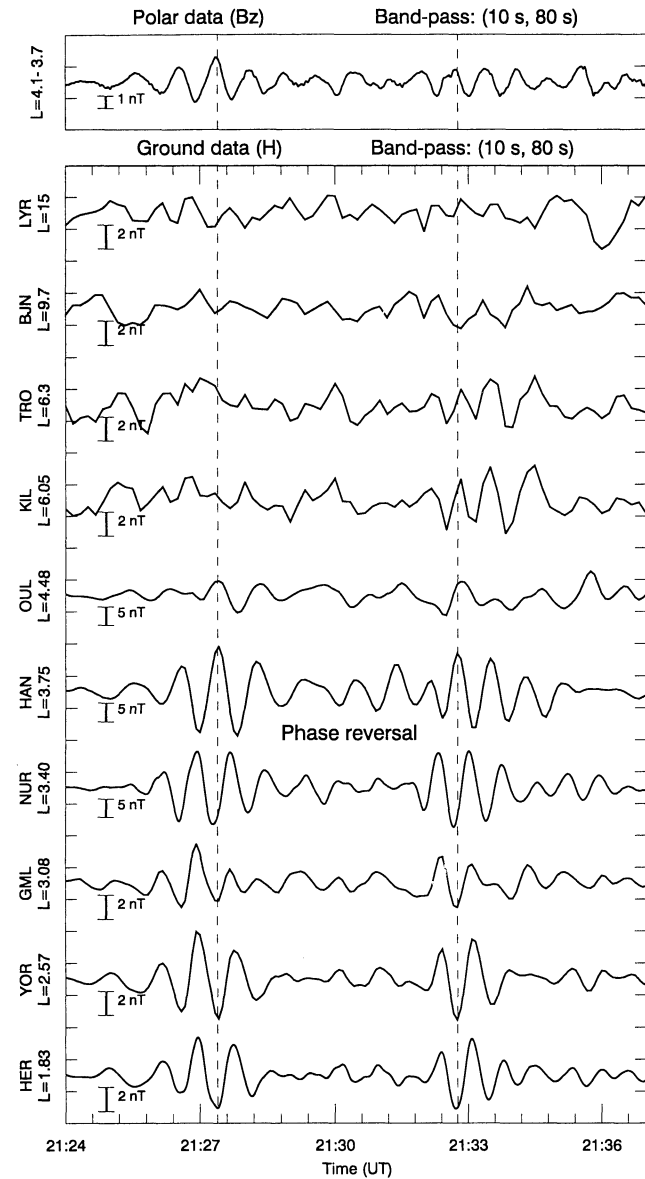
Figure 5. Comparison of Pi2 waveforms in space and on the ground on May 1, 1997. The data were band-pass filtered (10 and 80 s). The top panel shows the compressional component of the magnetic field as recorded by Polar. The remaining panels show the band-pass-filtered H component of the ground magnetic field from Plate 1. A phase reversal is indicated (see text for further description). The vertical dashed lines are drawn as a visual aid. Note that the scales and time resolutions (see section 2) are different for different panels.

($\leq$10). These theoretical results are consistent with our observations (see section 6 for further discussion).

The amplitude variation of the H component for both Pi2s is explicitly shown in Figure 6. Although the coherence is much less for stations with $L \geq 4$, their signal amplitudes are included as well. The amplitude peaks near HAN for both Pi2 events. The power at higher-latitude stations falls off rapidly; a little less so for lower-latitude stations. The peak in the amplitude profile is well documented in the literature, where it is referred to as the Pi2 secondary amplitude maxi-

mum. First observed by *Jacobs and Sinno* [1960], its cause has been ever since under investigation. In addition to this amplitude peak, we already showed in Figure 5 the existence of a 180° phase reversal of the H component, the location of which coincides with the location of the amplitude peak. These two properties are characteristics of FLR as demonstrated by theoretical studies [*Hughes and Southwood*, 1976] and ground-based observations of Pc pulsations [e.g., *Samson et al.*, 1992b]. As shown in section 4, Polar observed FLR close to the L value where the ground data suggest FLR.

Figure 6 also shows that Glenmore (GML) recorded smaller-amplitude oscillations than the surrounding stations. Hence it could be that GML is located close to an H minimum associated with the node of a radially standing compressional wave in the magnetosphere. The phase relationship in this case is such that oscillations at both the inner and outer regions with respect to the location of the node are in phase while a 180° phase shift is present at the node. *Yeoman and Orr* [1989] observed this ground signature and concluded that the Pi2 were due to a cavity mode. The fact that the oscillations at stations with $L \leq 3.08$ were exactly in phase supports this view for the Pi2 on May 1, 1997. The
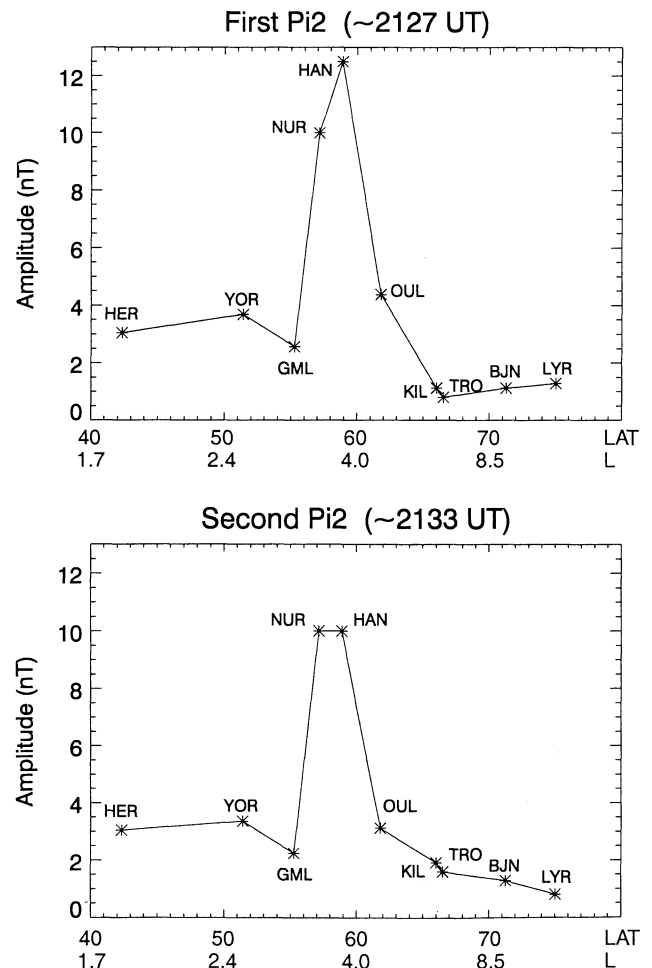

Figure 6. The amplitudes of the H component (filtered between 10 and 80 s) from different ground stations plotted as a function of latitude and L value.
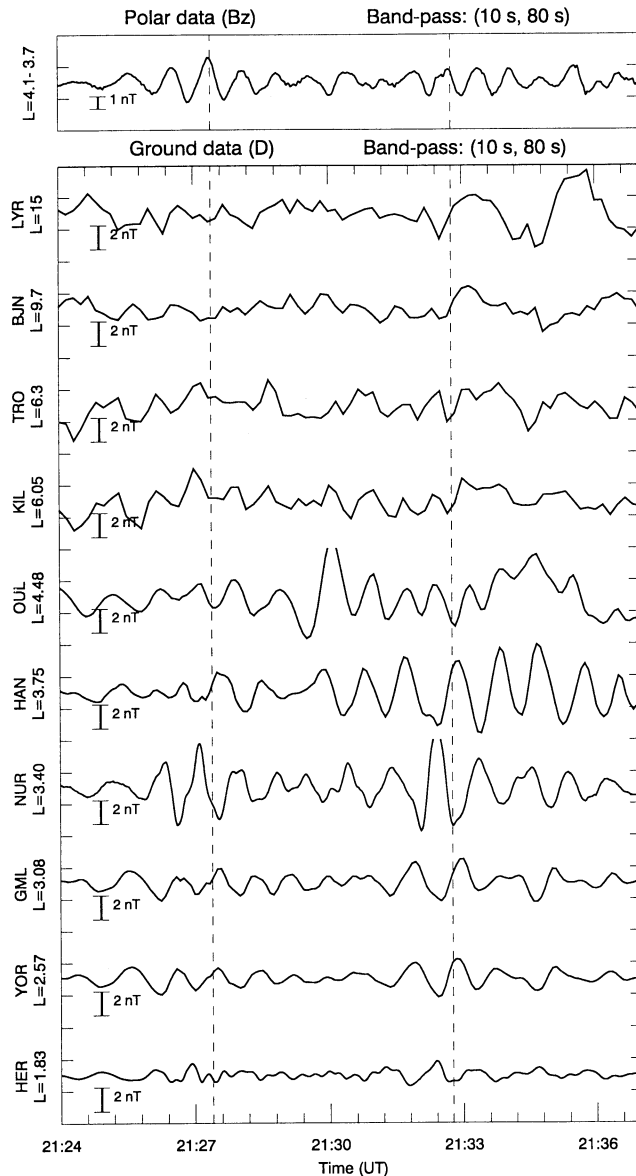
Figure 7. Same format as in Figure 5 but showing the D component of ground magnetic field data.

reason why the phase shift does not show in our data might be because the actual H minimum (due to the standing compressional wave) overlapped with the amplitude maximum of the FLR and is thus not visible. We are aware that this scenario is somewhat speculative. The interpretation of ground data with respect to the MHD modes is often ambiguous, owing to the effect of the ionosphere on MHD wave propagation. Because a fast mode signal does not undergo a rotation but the components of a FLR rotate by 90° in the ionosphere [*Hughes*, 1974], a separation of these two wave modes is often ambiguous on the ground. On the basis of satellite and ground data, we suggest that the amplitude and phase variation of the H component are due to the simultaneous occurrence and interference of the compressional cavity-type mode and FLR (see also section 6 for further discussion).

Despite the fact that the amplitude and phase signature recorded in the ground data H component are consistent with FLR, an inspection of the corresponding D component complicates this interpretation. Figure 7 shows the D component ground data of the same stations and in the same format as Figure 5. For comparison we again included the compressional component of the magnetic field measured by Polar in the top panel. Oscillations were also observed over a wide range of latitude. The following discussion is limited to stations with $L \leq 4$. The dominant periods in H and D for the first Pi2 were identical. For the second Pi2, on the other hand, the period of D was longer than that of H, suggesting that H and D component Pi2 waves can be excited independently. *Lester and Orr* [1983], for example, also reported cases of Pi2 where H and D were decoupled. The amplitudes are largest at HAN and NUR as was also the case for the H component. Whereas the H component showed only one 180° phase shift at the L value between HAN and NUR, the phase of the D component underwent a number of 180° phase shifts in latitudinal direction. Most importantly, a phase reversal of $\sim 180°$ was also present between HAN and NUR. The effect of this is that the sense of polarization in the H-D plane did not change across the amplitude peak in the H component as one could have inferred from the H component (Figure 5) alone. Although a change of polarization sense has theoretically been shown to occur in space across a FLR [*Southwood*, 1974], and observational evidence of this reversal exists on the ground [e.g., *Samson et al.*, 1971; *Fukunishi*, 1975], a theoretical study by *Hughes and Southwood* [1976] also shows that the effect of atmosphere and ionosphere on FLR can be such that the polarization reversal at the resonance is lost on the ground. Hence, on the basis of both components, H and D, the amplitude peak could nevertheless be caused by FLR.

Real polarization reversals on the ground for the Pi2s on May 1, 1997, are observed at other latitudes. Figure 7 shows phase shifts of $\sim 180°$ in the D component between HER and YOR (stations in opposite hemispheres) and between GML and NUR. These phase shifts are not accompanied by phase shifts in H, thus resulting in full polarization reversals. The latitudinal phase variation of D is rather complex for the Pi2s on May 1, 1997. These observations differ from phase measurements of three Pi2 events reported by *Yeoman and Orr* [1989]. The authors reported two events with a phase shift of $\sim 180°$ in H at $\sim 57°$ magnetic latitude ($L\sim 3.37$) with the phase of D being nearly constant between $\sim 50°$ and 58° magnetic latitude. In the third event the phases of both H and D were constant between $\sim 50°$ and 60° magnetic latitude ($L\sim 2.42$ and 3.56). Only a few studies have investigated D component Pi2 pulsations. We believe that the differences in the H and D Pi2 pulsations reported herein warrant a further investigation in a future study.

As evidence that the same Pi2 pulsations were also observed on the dayside, we present band-pass-filtered ground data from Makaha station (MAK, L=1.17) and Kakioka station (KAK, L=1.17) in Figure 8. MAK and KAK were located at ~ 1030 MLT and ~ 0612 MLT at the time of the Pi2s, respectively. The first curve of Figure 8 shows MAK magne-
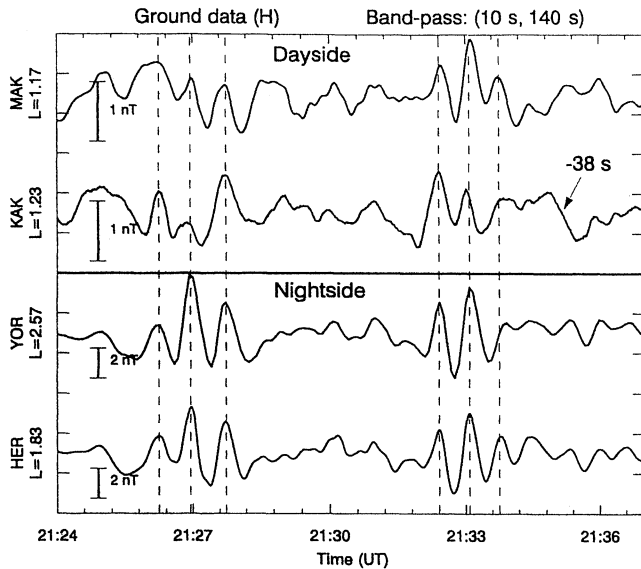
Ground data (H)   Band-pass: (10 s, 140 s)

Figure 8. Comparison of dayside and nightside ground magnetic field records (*H* component) for the Pi2s on May 1, 1997. The signal at MAK (~1030 MLT) occurred simultaneously and was very similar to those at YOR and HER (~2130 MLT). In contrast, the signal at KAK (~0612 MLT) was delayed by 38 s with respect to the signals at YOR and HER. The data were band-pass-filtered (10 and 140 s). The vertical dashed lines are drawn as a visual aid.

tometer data (*H* component). The second curve shows KAK data (*H* component) time-shifted by minus 38 s. For comparison, the third and fourth curves show ground data from the low-latitude stations YOR and HER, located in the nightside (~2130 MLT). The vertical dashed lines were drawn as a visual aid. The signal at MAK occurs simultaneously and is very similar to those at YOR and HER. The simultaneous occurrence of dayside and nightside Pi2 pulsations at low latitudes has been reported by *Sutcliffe and Yumoto* [1989] and *Shinohara et al.* [1997], for example. Hence the Pi2s

reported herein are likely of the same type. In contrast, the signal at KAK is delayed by 38 s with respect to the signals at YOR and HER. If we allow for this time delay, the signals show very similar features in their waveforms. We hence conclude that the same Pi2 pulsations were observed at three globally separated local times (~2118, ~0612, and ~1030 MLT). The 38-s time delay between the stations may be interpreted by propagating Pi2 waves in the longitudinal direction or an azimuthal wave structure of a cavity-type mode (see section 6 for further discussion).

6. Summary and Discussion

In this paper we reported simultaneous observations of two successive substorm-related Pi2 pulsations in space (~2300 MLT, L~3.7-4.1, and MLAT~10-14°) and on the ground in the nightside (2130-2330 MLT, $1.83 \leq L \leq 15$) and in the dayside (~1030 MLT, L=1.17, and ~0612 MLT, L=1.23). The nightside ground data showed monochromatic oscillations (~20 mHz) in H over a large latitudinal range. Most of the wave power, however, was confined within $L \leq 4.5$. Identical Pi2 pulsations in the transverse and the compressional modes were recorded by Polar. Although both Pi2s showed very similar signatures on the ground, the space signature showed differences. Electric and magnetic field measurements from Polar showed the presence of standing shear Alfvén waves for both Pi2s. Interestingly, whereas the first Pi2 showed standing compressional waves, the second Pi2 following only ~6 min later was a propagating compressional wave. This is the first identification of the fast mode structure on the basis of in situ electric and magnetic field measurements in association with typical ground Pi2 pulsations during substorms. The important result is the confirmation in space of FLR being coupled to a radially trapped fast (compressional) mode and a propagating fast mode (Figure 9). Mode-coupled FLR have been predicted [*Chen and Hasegawa*, 1974; *Southwood*, 1974; *Kivelson and Southwood*, 1986] but have not been reported in association
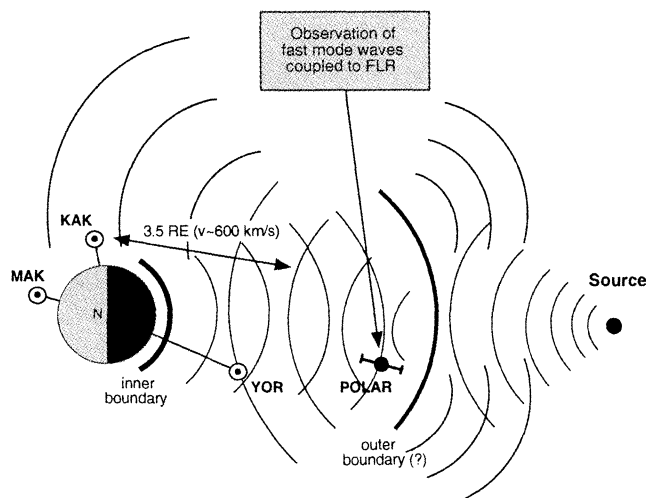

Figure 9. One possible scenario to explain ground- and satellite-based observations of the May 1, 1997, Pi2 pulsations.

with Pi2 pulsations. The peak Poynting flux associated with the FLR was $\sim$20 μW m^{-2}. A net Poynting flux perpendicular to the ambient magnetic field of the fast mode wave was present and was directed away from the Earth and in an easterly direction. The antisunward direction can be explained by assuming a more efficient inner boundary for the reflection of compressional waves than the outer reflector, if one assumes an imperfectly trapped fast mode for the first Pi2. A possible inner boundary is either the ionosphere or the conducting surface of the Earth [e.g., *Itonaga et al.*, 1997]. For the second Pi2 no interference of incident and reflected wave had occurred. Because the fast mode wave showed a similar net energy flow as for the first Pi2, i.e. away from the Earth, it is likely that Polar only observed the reflected wave. In general, a net Poynting flux is expected for the energy transfer from the fast mode to the FLR [*Kivelson and Southwood*, 1986].

The nightside ground data showed a strong amplitude maximum and a phase reversal in the H component between L=3.4 and 3.75. Previous studies based on ground data have attributed the 180° phase shift to cavity modes [*Yeoman and Orr*, 1989], FLR [*Fukunishi*, 1975], and surface waves on the plasmapause [*Sutcliffe*, 1975]. A comparison of ground data, as reported herein, with theoretical predictions for the amplitude and phase variations of the FLR model and the cavity-type mode model, as described in section 1, favors the FLR interpretation over the cavity-type mode as the source of the amplitude maximum for the Pi2 events on May 1, 1997. The magnetically conjugate signature of FLR in space observed by Polar supports this view. If the space FLR was indeed causing the amplitude maximum in the H component ground data and the plasmapause was located at lower L value than the Pi2s (for which there was some data support; but we could not conclusively confirm this), then the surface wave model can be ruled out as the source of the amplitude maximum. With regard to the FLR, one concern might be the lack of a gradual phase change in the latitudinal direction in the ground data, which is a typical feature of FLR. However, FLR are narrow structures with characteristic half-widths of 0.2-0.3 L at midlatitude [*Menk et al.*, 1999]. Hence the spatial separation of the ground stations used in this study might have simply been too large to show intermediate phase changes.

Allowing for very localized FLR (between $L\sim$3.4 and 3.75), ground data suggest that the pulsations at $L \leq 3.08$ were caused by the compressional waves that were observed by Polar. These waves showed standing as well as propagating signatures in space. In particular, for the first Pi2, which were standing compressional waves in space, the amplitude and phase variation on the ground agrees with a cavity-type mode interpretation. We reported a constant phase (0°) for low-latitude stations ($L \leq$3.08) and a possible indication of an amplitude minimum close to $L \sim$3.08. The actual minimum and the associated phase shift of 180° due to a radial compressional structure of the cavity-type mode might have been masked by the simultaneous presence of the FLR, which was possibly superimposed on the compressional ground signal.

We reported that the period of oscillations in D and H did not match throughout for the Pi2 pulsations on May 1, 1997. It further seems to suggest that H and D component Pi2 waves can be excited independently [*Lester and Orr*, 1983]. Furthermore, the phase signature of the D component was more complicated. At this time we have no explanation for these observations other than that we believe that the interaction of FLR and fast mode wave might yield complicated ground signals which do not necessarily follow model results of the FLR model and the cavity-type mode model studied in a decoupled fashion.

The Pi2 pulsations were also observed on the dayside at two low-latitude, longitudinally separated ground stations. One station, located at $\sim$1030 MLT, recorded two Pi2 pulsation events simultaneously to those recorded in the nightside with very similar waveform. A global cavity mode has been suggested by *Sutcliffe and Yumoto* [1989] as a mechanism for the simultaneous occurrence of dayside and nightside Pi2 pulsations. Alternatively, the second dayside station, located at $\sim$0612 MLT, also recorded two similar Pi2 pulsation events. However, the pulsations were delayed by 38 s. This phase delay is consistent with the propagation time of fast mode waves from the nightside to the dayside ground stations. Since fast mode waves can travel across magnetic field lines, the shortest distance from the field line conjugate to Kakioka and the nightside is $\sim$3.5 R_E, yielding a speed of 600 km s^{-1}, which is a reasonable value for fast mode waves in the plasmasphere. Therefore a possible scenario could be that fast mode waves launched in the outer magnetosphere penetrate a potential barrier. These waves are then partially trapped between an inner boundary and an outer boundary, establishing standing waves, which were observed by Polar for the first Pi2 event. Because of the finite cross section of these boundaries and the lack of boundaries in the azimuthal direction, fast mode waves can leave the resonance region, hence leading to a rapid decay of the pulsations [*Takahashi et al.*, 1995]. These lost traveling waves at the resonance frequency subsequently cause forced oscillations of field lines along their propagation path (Figure 9, KAK). An alternative explanation is based on the azimuthal wave structure of a global cavity mode. The simulations by *Lee and Lysak* [1999] investigating the local time dependence of signal time series due to a plasmaspheric cavity mode showed that phase shifts can occur around the globe at low latitude.

Because we were neither able to unambiguously identify the plasmapause location as the outer boundary nor able to identify any other outer boundary, we refer to the observed magnetospheric resonance as a radially trapped fast mode wave with unknown outer reflection boundary. A key signature of a trapped fast mode is standing compressional waves. Standing wave structures can also be set up when the outer boundary is subject to forced oscillations [*Takahashi et al.*, 1992]. Such a driver could be bursty bulk flow as proposed by *Kepko and Kivelson* [1999] in association with Pi2 pulsations. Since it was not possible to conclusively determine the plasmapause, we cannot rule out this possibility as the generation mechanism for the first Pi2 event. Similarly, the second Pi2 event, which showed propagating compressional

waves in space, could be a candidate for a driver mechanism.

The Pi2 pulsations on May 1, 1997, can be compared to the statistical study on Pi2 pulsations in space by *Takahashi et al.* [1995], using the AMPTE/CCE satellite. Among other results, they found that the Pi2 pulsations were primarily poloidal. The power and phase variation as a function of L value ($2 \leq L \leq 5$) of the poloidal component was consistent with the structure of a cavity-type mode resonance with a node in the compressional component near $L=4$. For the Pi2s on May 1, 1997, we could not absolutely confirm the presence of a node in H, although there was an indication for it. As argued before the possibility of simultaneous FLR on the ground might have masked the node structure on the ground. Furthermore, Takahashi et al. did not find a toroidal mode. The absence of a toroidal oscillation is not necessarily inconsistent with our observation. It might just show that it is very rare to observe FLR, owing to its limited spatial extent in the L direction.

Similar to the Pi2 events described herein, the study by *Osaki et al.* [1998], using the Akebono satellite, characterized both electric and magnetic fields of two successive Pi2 pulsations in the plasmasphere together with ground data. The most important difference from our observations is that the Pi2s observed by Akebono were due to traveling Alfvén waves as opposed to standing Alfvén waves. The associated Poynting flux propagated along magnetic field lines only in one direction towards the ionosphere. The Poynting flux was approximately one tenth of the flux reported herein for the May 1, 1997, Pi2 pulsations. The authors estimated damping rates for the Pi2 pulsations due to the traveling Alfvén wave, and they concluded that a cavity mode could not have sustained the Pi2 oscillations, and hence an external driver was considered more probable. Additional differences were that no compressional component was detected by the Akebono satellite. The period of the pulsations was 90 s. Akebono's observation was made at a higher magnetic latitude ($24°$-$40°$) but similar local time (~ 2240 MLT). No comments were made as to whether a phase reversal on the ground was present or not. The results by *Osaki et al.* [1998] and our results, in particular the differences, show the importance of simultaneous ground and satellite measurements of Pi2 pulsations. The global nature of these pulsations can currently best be studied by ground stations, whereas the electrodynamics of the pulsations requires in situ electric and magnetic field measurements.

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